Joint CIB - IAARC Commission on “Customized Industrial Construction”

Proceedings of the CIB*IAARC W119 CIC 2016 Workshop

“Advanced Construction and Building Technology for Society”

General Chair:

Thomas Bock (Prof. Prof. h. c./SRSTU Dr.-Ing./Univ.Tokio)

Co-Chair:

Alexey Bulgakov (Prof. Dr.-Ing. hab.)

Paper Review Board:

Christos Georgoulas (Dr.-Ing.)
Thomas Linner (Dr.-Ing.)
Katharina Langosch (Dr.-Ing.)
Jörg Güttler (M.Eng)

Sponsors

TÜV Süd

Institute of Advanced Study, TUM

27 Oct 2016

Chair for Building Realization and Robotics 
Technische Universität München (TUM), Germany
Preface

CIB Working Commission, W119 on ”Customized Industrial Construction” has been established as the successor of former TG57 on Industrialization in Construction and as a joint CIB-IAARC Commission. Prof Dr Ing Gerhard Girmscheid, ETH Zurich, Switzerland (Coordinator of the former TG57) and Prof Dr Ing Thomas Bock, Technische Universitat Munchen, Germany are the appointed Coordinators of this Working Commission. The workshop is hosted by the Chair for Building Realization and Robotics located at TUM within the Bavarian high tech cluster, the Master of Science Course ”Advanced Construction and Building Technology” and by IAARC-Academy representing the research training program of the International Association for Automation and Robotics in Construction (IAARC). The workshop will concentrates international researchers, practitioners and selected top-students coming from 8 different professional backgrounds (Architecture, Industrial Engineering, Electrical Engineering, Civil Engineering, Business Science, Interior Design, Informatics, Mechanical Engineering)

Industrialization in Construction will become more customer oriented. Systems for adaptable manufacturing and robot technologies will merge the best aspects of industrialization and automation with aspects of traditional manufacturing. Concepts of mass customization can be implemented via the application of robots in construction and building project/product life cycle as prefabrication processes, on site and in service as socio technical systems. Topics include, but are not limited to the following aspects of Automation and Robotics in Construction:

- Industrialized Customization in Architecture: Mass Customization onsite, Factory Production, Logistics and Factory Networks, Production
- Logistics/Site Automation and Robotics: Mass Customization on site, Site Automation, Site Robotics, Site Logistics for Automation, Systems and Technologies, Automation and Robot oriented Site Management
- Automation and Robot Oriented Design: Design and Buildings Structures Enabling efficient use of Automation and Robotics, Modularization, Product Structure, Building Information Modeling

October 24, 2016

Thomas Bock
Munich
Author Index

Andaloro, Michele 36
Argiolas, Alfredo 14
Bock, Thomas 1, 20, 45, 59
Brell-Cokcan, Sigrid 20
Bulgakov, Alexey 8
Follini, Camilla 45
Greschner, Karl 52
Hu, Rongbo 1
Iturralde, Kepa 20, 28, 52, 59
Komotori, Hirokazu 67
Kruglova, Tatiana 8
Linner, Thomas 1, 20, 45, 59
Lublasser, Elisa 20
Ma, Jing 28
Meschini, Silvia 59
Mita, Akira 67
Nadim, Wafaa 45
Niccolini, Marta 14
Pan, Wen 45
Panahikazemi, Lila 36
Ragaglia, Matteo 14
Rossi, Andrea 36
Ruttico, Pierpaolo 36
Sato, Masayuki 74
Sayfeddine, Daher 8
## Keyword Index

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affinity</td>
<td>67</td>
</tr>
<tr>
<td>Affordable and Adaptable Building System</td>
<td>45</td>
</tr>
<tr>
<td>Automatic Assembly</td>
<td>28</td>
</tr>
<tr>
<td>Automation</td>
<td>8, 20, 59</td>
</tr>
<tr>
<td>BIM</td>
<td>59</td>
</tr>
<tr>
<td>Biofied building</td>
<td>67</td>
</tr>
<tr>
<td>Building Technology</td>
<td>59</td>
</tr>
<tr>
<td>Construction</td>
<td>8, 59</td>
</tr>
<tr>
<td>Construction Machines</td>
<td>14</td>
</tr>
<tr>
<td>Contingency</td>
<td>67</td>
</tr>
<tr>
<td>Crane System</td>
<td>52</td>
</tr>
<tr>
<td>Decentralized Processing Units</td>
<td>45</td>
</tr>
<tr>
<td>Deconstruction</td>
<td>20</td>
</tr>
<tr>
<td>Dense Areas</td>
<td>52</td>
</tr>
<tr>
<td>End-effector</td>
<td>52</td>
</tr>
<tr>
<td>End-of-life</td>
<td>20</td>
</tr>
<tr>
<td>environmental design for children</td>
<td>74</td>
</tr>
<tr>
<td>Fabrication</td>
<td>36</td>
</tr>
<tr>
<td>Façade</td>
<td>28</td>
</tr>
<tr>
<td>Furniture</td>
<td>74</td>
</tr>
<tr>
<td>height of space</td>
<td>74</td>
</tr>
<tr>
<td>Inverse Kinematics</td>
<td>14</td>
</tr>
<tr>
<td>Joint Saturations</td>
<td>14</td>
</tr>
<tr>
<td>Kinect v2</td>
<td>67</td>
</tr>
<tr>
<td>Kinematic Singularities</td>
<td>14</td>
</tr>
<tr>
<td>Lightweight System</td>
<td>28</td>
</tr>
<tr>
<td>Logistics</td>
<td>52</td>
</tr>
<tr>
<td>Mass Customization</td>
<td>36</td>
</tr>
<tr>
<td>Mathematical Model</td>
<td>8</td>
</tr>
<tr>
<td>Mechatronic Formwork</td>
<td>8</td>
</tr>
<tr>
<td>Modularity</td>
<td>1</td>
</tr>
<tr>
<td>Mold Design</td>
<td>36</td>
</tr>
<tr>
<td>Monolithic Structure</td>
<td>8</td>
</tr>
<tr>
<td>Keyword</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Panel System</td>
<td>52</td>
</tr>
<tr>
<td>Plug-and-play</td>
<td>1</td>
</tr>
<tr>
<td>Prefabrication</td>
<td>20</td>
</tr>
<tr>
<td>Refurbishment</td>
<td>20</td>
</tr>
<tr>
<td>Renovation</td>
<td>1, 28</td>
</tr>
<tr>
<td>Requirements Engineering</td>
<td>45</td>
</tr>
<tr>
<td>Robot</td>
<td>67</td>
</tr>
<tr>
<td>Robot Motion Programming</td>
<td>20</td>
</tr>
<tr>
<td>Robot swarm</td>
<td>1</td>
</tr>
<tr>
<td>Robotics</td>
<td>8, 20, 28, 36, 59</td>
</tr>
<tr>
<td>ROS</td>
<td>59</td>
</tr>
<tr>
<td>Single-task Construction Robots (STCRs)</td>
<td>1</td>
</tr>
<tr>
<td>Teleoperation</td>
<td>14</td>
</tr>
<tr>
<td>Urban Farming</td>
<td>28</td>
</tr>
<tr>
<td>Variability</td>
<td>67</td>
</tr>
</tbody>
</table>
# Table of Contents

SMARTBEE: A Framework of Single/Multi-task On-site Adaptable Renovation Robot Technology for Building Engineering Enhancement ........................................... 1  
   *Rongbo Hu, Thomas Linner and Thomas Bock*

Simulation Mathematical Model of Mechatronic Sliding Formwork for Monolithic Tower with Variable Cross Section ....................................................... 8  
   *Alexey Bulgakov, Tatiana Kruglova and Daheer Sayfeddine*

Inverse Kinematics for Teleoperated Construction Machines: a Novel User-oriented Approach ................................................................. 14  
   *Matteo Ragaglia, Alfredo Argiolas and Marta Niccolini*

Automated Refurbishment & End-of-life Processes – Research Approaches in German and Japanese Construction .................................................. 20  
   *Elisa Lublasser, Kepa Iturralde, Thomas Linner, Sigrid Brell-Cokcan and Thomas Bock*

   *Jing Ma and Kepa Iturralde*

Innovative Methods for Mold Design and Fabrication .............................................. 36  
   *Pierpaolo Ruttico, Andrea Rossi, Lila Panahikazemi and Michele Andaloro*

Development of a Methodology based on Requirements Engineering for Informal Settlements upgrading in Cairo .............................................. 45  
   *Camilla Follini, Wen Pan, Thomas Linner, Wafaa Nadim and Thomas Bock*

Restoration System For Buildings In Dense Areas ............................................. 52  
   *Karl Greschner and Kepa Iturralde*

Novel Applications offered by Integration of Robotic Tools in BIM-based Design Workflow for Automation in Construction Processes .................. 59  
   *Silvia Meschini, Kepa Iturralde, Thomas Linner and Thomas Bock*

Affinity of a Home Robot ................................................................. 67  
   *Hirokazu Komotori and Akira Mita*

Design of Equipment and Furniture for Children based on their Height ............... 74  
   *Masayuki Sato*
SMARTBEE: A Framework of Single/Multi-task On-site Adaptable Renovation Robot Technology for Building Engineering Enhancement

Rongbo Hu¹, Thomas Linner¹, and Thomas Bock¹

¹Chair for Building Realization and Robotics, Technical University Munich, Germany
* Corresponding author (rongbo.hu@br2.ar.tum.de)

In recent years, due to the challenge of population ageing, labor shortage and globalization, robots and automation have been playing an increasingly important role in the construction industry. Yet in German construction industry, of which 80% are renovations, most application examples are single-task approaches such as component production and prefabrication, few can be seen as versatile, flexible, and multifunctional solutions which adapt the increasing need of on-site robots. On the basis of comprehensively categorizing and analyzing the current application examples of state-of-the-art single-task construction robots (STCRs), this paper aims to propose a framework of flexible and universal platform combining single-task robots as a robot swarm focusing on renovation (Single/Multi-task On-site Adaptable Renovation Robot Technology for Building Engineering Enhancement, or simply SMARTBEE). The interaction between the robots and humans will also play a major role. Research focus will be on the development of anticipatory assistive controllers to support human labor, on shared control architectures, and the integration of wearable haptics as human-robot interface. Furthermore, the research will concentrate on developing controllers for the safe operation of modular robotic solutions. This will also incorporate considering the predicted movements of surrounding workers to ensure safe operation of construction robots. For the control of modular robots, a plug-and-play functionality will be envisioned which allows one to change the configuration of construction robots while the new kinematics and control is adapted on the fly. The objective of this proposed framework is to establish a consortium to rigorously develop the concept of flexible modular robots incorporating human assistive functions to fill the vacancy in the construction robot industry. The research priority will be given to STCRs, On-site Logistic/Distribution, Renovation Technology, and control engineering.

Keywords: Single-task Construction Robots (STCRs), Renovation, Robot swarm, Plug-and-play, Modularity

INTRODUCTION
In recent years, Germany’s birth rate has collapsed to the lowest level in the world, and thus its shrinking workforce will seriously start threatening the long-term sustainability of Europe’s leading economy. Meanwhile, robots and automation will play an increasingly important role in the construction industry in the near future. Yet in German construction industry, of which 80% are renovations, most application examples are single-task approaches such as component production and prefabrication, but few can be seen as versatile, flexible, and multifunctional solutions which adapt the increasing need of on-site robots.

With the economic boom in Japan in late 1970s, the big Japanese construction companies, known as the “Big Five” (i.e. Shimizu, Taisei, Kajima, Obayashi, and Takenaka), perceived a huge potential in construction robotics and automation. Each of them used approximately 1% of its annual gross revenue of over $15 billion for research and development including establishing campus-like research and development facilities where advanced technologies were developed and tested. This gives Japan a boost in the development of construction robot technology¹. Single-task construction robots (STCRs) were developed primarily for the use on construction site to imitate skilled labor. Until today there are more than one hundred STCRs developed, most approaches are designed to substitute human construction activities which are considered difficult, dirty, and dangerous. To be specific, these robots can help to do a variety of repetitive, dangerous or sophisticated works, easing pressures on labor shortage and skill mismatch. Gradually, more emphasis has been placed on integrated construction automation rather than single-task approaches due to various admitted limitations of STCRs such as high R&D costs, long development time, high maintenance costs, highly specific functions, a lack of collaboration with human beings, and low level of integration (see Fig. 1).

However, recent trend shows that major Japanese construction companies are gradually returning to single-task-like approaches. For instance, although suspending the integrated and automated construction site (i.e. ABCS) as a total system, Obayashi applies some of its subsystems as STCRs (e.g. welding systems, automated logistics systems, etc.). Rather than directly combining those subsystems, Obayashi obtains workshop-like flexibility in order to better adapt to more complex construction situation such as Tokyo Skytree, of which the shape changes several times from bottom to top. Today, the application of innovative management approaches, the optimization of work process, the performance im-
Improvements of hardware and software, and the rigorous challenges of population ageing allow the revitalization and rejuvenation of STCRs. The development and deployment of STCRs thus become more relevant and important than ever before.

![Fig.1. Brief timeline showing various institutions' participation in developing STCR systems since the 1970s (refined and complemented figure on the basis of Cousineau & Miura, 1998 and Hasegawa, 1999)](image)

<table>
<thead>
<tr>
<th></th>
<th>1970s</th>
<th>1980s</th>
<th>1990s</th>
</tr>
</thead>
<tbody>
<tr>
<td>JARA</td>
<td>Initiation &amp; Concept</td>
<td>Surveys &amp; Research</td>
<td></td>
</tr>
<tr>
<td>Waseda University</td>
<td>WASCOR2</td>
<td>WASCOR3</td>
<td>WASCOR3</td>
</tr>
<tr>
<td>University of Tokyo</td>
<td>R&amp;D in Prefabrication</td>
<td>R&amp;D Robot-Oriented Design/Structured Environments</td>
<td></td>
</tr>
<tr>
<td>MOC</td>
<td>Use of Mechatronics in Construction</td>
<td>R&amp;D Technology</td>
<td></td>
</tr>
<tr>
<td>AIJ</td>
<td></td>
<td>Surveys &amp; Research</td>
<td></td>
</tr>
<tr>
<td>BCS</td>
<td></td>
<td></td>
<td>Surveys &amp; Research</td>
</tr>
<tr>
<td>ACTEC</td>
<td></td>
<td>Surveys &amp; Research in Robot Technology</td>
<td></td>
</tr>
<tr>
<td>JSCE</td>
<td></td>
<td>Surveys, Research, &amp; Training</td>
<td></td>
</tr>
<tr>
<td>Conferences</td>
<td>Scientific Conferences, Symposia, &amp; Proceeding IAARC/ISARC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contractors</td>
<td>Involvement of R&amp;D institutes: Shimizu, Fujita, Obayashi, Taisei, Kajima, Takenaka, Maeda, etc.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STATE OF THE ART**

**Automation/robotics in the construction/renovation fields**

The application of automation and robotic systems in the construction industry is lagging greatly behind compared to that in other industries and is mainly seen in the fields of component production and prefabrication. In Japan, Korea and Scandinavian countries, there are approaches using single-task construction robot systems such as facade installation or construction of the structure of high-rise buildings. In Europe, robotic systems are not usually used on site or in the interior construction or renovation beyond the research status. Newer approaches in research at the international level aimed at the use of humanoid robots for interior design and the use of automated systems for demolition.

On the basis of categorizing and analyzing the current application examples of state-of-the-art (STCRs) for renovation, this paper aims to propose a framework of a multifunctional and universal platform combining single-task robots as a robot swarm focusing on renovation (Single/Multi-task On-site Adaptable Renovation Robot Technology for Building Engineering Enhancement, or simply SMARTBEE). The interaction between the robots and humans will also play a major role. Research focus will be on the development of anticipatory assistive controllers to support human labor, on shared control architectures, and the integration of wearable haptics as human-robot interface. Furthermore, the research will concentrate on developing controllers for the safe operation of modular robotic solutions. This will also incorporate considering the predicted movements of surrounding workers to ensure safe operation of construction robots. For the control of modular robots, a plug-and-play functionality will be envisioned which allows one to change the configuration of construction robots while the new kinematics and control is adapted on the fly. The objective of this proposed framework is to establish a consortium to rigorously develop the concept of flexible modular robots incorporating human assistive functions to fill the vacancy in the construction robot industry. The research priority will be given to STCRs, On-site Logistic/Distribution, Renovation Technology, and control engineering.
How this SMARTBEE addresses the shortcomings of previous approaches

Shortcoming 1: Despite the evident improvement of productivity and working conditions, the categories of single-task construction robots (STCRs) are highly specific, not only to a profession, but even to a task within a specific profession, which results in cost-ineffective, time-consuming and overlapping research and developing processes. Therefore, there has been an urgent demand that the design of STCRs should embrace modularity and adaptability that promote efficiency and usability. Thus, the design of SMARTBEE will particularly focus on promoting modularity and adaptability within the system. For the control of modular robots, a plug-and-play functionality will be envisioned which allows one to change the configuration of construction robots while the new kinematics and control are adapted on the fly.

Shortcoming 2: The process of construction automation is difficult due to its high complexity. Yet various functionalities have been realized in STCRs, few research has addressed the optimization of how those STCRs can coordinate seamlessly and how the efficiency of the collaboration of STCRs would be maximize. Thus, the research will concentrate on developing controllers for the safe operation of modular robotic solutions. This will also incorporate considering the predicted movements of surrounding workers to ensure safe operation of construction robots. Meanwhile, researchers have proposed a number of innovative state-of-the-art schemes in the academic field, such as Complex Control\(^4\), Automatic Modular Assembly System (AMAS)\(^5\), Collective Construction with Robot Swarms\(^6\), yet few have been applied in the construction industry. Eventually, this framework intends to bridge the gap between academia and industry by integrate state-of-the-art research into a compact, flexible, and versatile platform.

Shortcoming 3: The use of automation and robots on the site has been mainly held back by the lack of flexibility of the system and incompatibility with human labor and other parallel processes on the construction site (the use of robots has required greater security areas, affecting other work nearby, etc.). It has also been criticized that existing approaches to robotization usually aim at the complete substitution of human labor. However, the demographic change in the construction industry shows a clear need for an innovative, highly flexible and self-adjusting assistive system to promote human craftsmanship. Therefore, it is necessary to assist and promote human labor in the platform by appropriate assistive haptic control functionalities that support exhaustive tasks. Also, the fully autonomous operation of robots in uncertain environments is still in far reach, in many aspects the decision support by the human is indispensable. Different modes of control sharing between the human and the robot that synergistically combine human intelligence with the robot force capacity and precision will be investigated. To this end, wearable haptics promises great and intuitive interaction as it provides appropriate feedback to the human about robot swarm internal states\(^7\). The integration of wearable haptics will be part of the research agenda.

OBJECTIVES

The paper aims to explore the potentials and to enhance the usability of STCRs in the building renovation industry. The main goal is to propose a universal platform of various STCRs in which the modularized end-effectors, joints and/or mobile bases can be replaced to adapt various functions. Daily work, in terms of on-site construction rather than administrative activities, will be supported. Through innovative solutions, obstacles can be overcome and great potentials will be achieved in labor productivity. Furthermore, developed from the research project, approaches to robotic-assisted design will revolutionize the traditional craftsmanship. In addition, cutting edge technologies such as exoskeleton will be integrated into the platform to further supplement the flexibility of the system. Thus the assemblers will be able to work longer hours more efficiently and meanwhile stay fit. Information technology and control engineering will provide valuable support to this platform. The results of SMARTBEE will have long-term positive effects on safety, efficiency, and economy of existing and future construction and related industries, as well as on the development of modularized and adaptable construction robot system.

METHODS

According to Bock and Linner (2016), existing STCRs can be defined into 24 categories according to their background behind development, operational capacity, control strategy and informational aspects, dimensions and workspace, relevant construction work process, and analysis of the composition and kinematic structures. They include: (1) automated site measuring and construction progress monitoring robots including mobile robots and aerial robots, (2) earth and foundation work robots, (3) robotized conventional construction machines, (4) reinforcement production/positioning, (5) automated 3D concrete structure on-site production, (6) automated 3D truss / steel structure on-site assembly, (7) bricklaying robots, (8) concrete distribution robots, (9) concrete levelling/compaction robots, (10) concrete finishing robots, (11) site logistic robots, (12) aerial robots for structure assembly, (13) swarm robotics and self-assembling building structures, (14) robots for positioning of components, (15) steel welding robots,
façade installation robots, (17) tile setting and floor finishing robots, (18) façade coating / painting robots, (19) humanoid construction robots, (20) exoskeletons / wearable assistive robots, (21) interior finishing robots, (22) fireproof coating robots, (23) service, maintenance, and inspection robots, (24) and renovation and recycling robots. On the basis of previous categorization, STCRs focusing on renovation can be further categorized as (1) site measuring robots, (2) tile setting and floor finishing robots, (3) façade coating / painting robots, (4) interior finishing robots, (5) fireproof coating robots, (6) logistic robots, and (7) renovation / recycling robots. Combining various renovation STCRs, a universal platform can be developed in which the modularized end-effectors, joints and / or mobile bases can be replaced to adapt various functions (See Fig. 2 & 3).

There are three primary research highlights in SMARTBEE platform: (1) designing feasible modularized and adaptive prototypes of STCRs; (2) developing controllers for the safe operation of modular robotic solutions; and (3) developing assistive haptic control, shared control architectures to support different levels of autonomy, and the integration of wearable haptics as human-machine-interface. STCRs can be seen as a kinematic structure which consists of the following components: a mobile base which enables the system to move (in some case a fixed base); an end-effector which enables various functions of the system; a rotary joint which allows the end-effector to rotate; a translational joint which allows the system to slide in a particular direction. SMARTBEE’s target is to develop a modularized STCRs system in which the major components such as mobile bases, translational & rotary joints, and end-effectors can easily be removed and replaced in accordance with various functions. Hardware platform interface (HPI) and application programming interface (API) of SMARTBEE must be accessible and standardized in order that the academia and industry will be able to further develop end-effectors with various functions, as well as in some cases mobile bases and translational / rotary joints. In addition, exoskeleton technology, in which reinforced human body can be seen as a very flexible mobile base as well as translational / rotary joints, will be integrated to the system in order to assist and enhance the efficiency of human labor (e.g. FORTIS exoskeleton, see Fig. 4.). Last but not least, a robust and feasible information and communications technology (ICT) platform which will improve the usability of the modular STCRs will be an essential feature to SMARTBEE system.

Fig.2. Integration of SMARTBEE platform

Fig.3. Modularized SMARTBEE robot system with various end-effectors

Fig.4. FORTIS exoskeleton, created by Lockheed Martin, can boost worker productivity up to 27 times. (Image: Photo Courtesy of Lockheed Martin. Copyright 2015)
By realizing the versatile universal platform combining modularized single-task robots for renovation, SMARTBEE will be applied especially to these scenarios: (1) Building surveying/inspection, (2) building façade coating / painting, (3) interior floor setting/replacing, (4) interior wall/ceiling painting, (5) façade fireproof coating, (6) wearable assistive devices, (7) site logistics (8) and recycling, etc. The research and development of SMARTBEE will particularly focus on promoting modularity, adaptability, and collaboration within the system (See Fig. 5).

**Implement**

A principal goal of the proposed system is to launch technology transfer process within the project duration and to foster dissemination into a variety of application fields. In order to achieve that goal, the willingness of companies and industries to enter into a cooperation and the success of individual applications will furthermore give the researchers important feedback on how to adjust the technical detail of SMARTBEE. In accordance with this activity, the potential for transferring the project results into a variety of industries and application fields will be enhanced.

On one hand, to maximize expertise and to successfully cooperate within Technical University of Munich (TUM), the core research team will consist of researchers from Chair of Building Realization and Robotics (BR2) 1), Chair of Robotics and Embedded Systems (i6) 10, and Chair of Information-oriented Control (ITR) 11 according to a signed agreement. In particular, firstly, the Chair of Building Realization and Robotics researches and consults in the field of advanced construction and building technologies. The mission of the Chair for Building Realization and Robotics is to extend the traditional core competences of design and build, broadening the activity area of future graduates, professionals and creating new employment opportunities. Located at TUM within the Bavarian high tech cluster, in which the chair is well connected, the chair functions as an incubator for the development and socio-technically integrated and building related technologies. Furthermore, chair members consistently contribute with high level publications to advancements in construction automation, Mass Customization, and Building Information Modelling. Therefore, the Chair of Building Realization and Robotics will mainly focus on designing feasible modularized and adaptive STCRs. Also, supporters of the technology diffusion process will be the consortia of the TUM-participated research projects such as BERTIM 12 and ZEROPLUS 13, and these consortia will closely collaborate with the research team to develop promising performance-enhancing features.

Secondly, the Chair of Robotics and Embedded Systems will mainly concentrate on developing controllers for the safe operation of modular robotic solutions. The Chair of Robotics and Embedded systems covers a broad range of research problems in robotics from perception to control and construction of robotic solutions. Specifically, the professorship “Cyber-Physical Systems” of Prof. Matthias Althoff focuses on guaranteeing safety of robotic systems and on realizing modular robotic systems, which both are key aspects of SMARTBEE system, to ensure the flexibility of robotic systems and meanwhile to guarantee safe operation in the presence of humans. Especially since all construction
projects involve human workers, safety is seen as an indispensable property. The safety aspect is researched in the EU project “UnCoverCPS” \(^{14}\) of which Prof. Matthias Althoff is the coordinator. Modular robots are researched in the Marie-Curie project “SMART-E” \(^{15}\). Thirdly, the Chair of Information-oriented Control will mainly concentrate on the development of assistive haptic control, shared control architectures to support different levels of autonomy, and the integration of wearable haptics as human-machine-interface. The Chair of Information-oriented Control focuses on the control and optimization in cooperative, networked, and distributed dynamical systems with application to robotics and human-machine interaction. The chair develops novel methods and tools for the analysis and control of such systems, which in particular consider model uncertainties as well as uncertainties and limitations in the data acquisition, communication, and computation. For this project particularly relevant is the research on human robot interaction, shared control, human-in-the-loop control and wearable haptics. Related research questions, however with different focus than in this proposed research, are addressed in the projects.

On the other hand, TUM’s close contact to technology oriented companies such as Deutsches Institut für Normung e.V. (DIN) \(^{16}\), Hans Schramm GmbH (Schramm) \(^{17}\), Zentralverband Sanitär Heizung Klima (ZVSHK) \(^{18}\), and YASKAWA Europe GmbH \(^{19}\), which can be considered as potential developers and/or operators of SMARTBEE, will allow for the efficient formation of research consortia that build upon the outcomes of this project. In general, the research and development of proposed framework will deliver profound technical, economic, and social impacts on the status quo of related fields. Furthermore, feasible business model will be discussed and proposed within the consortium. Due to the high cost of purchasing, leasing and service subscription modes can be the primary business model of SMARTBEE technology.

**Impact**

The outcomes of SMARTBEE system will generate manifold impacts on the status quo of the STCR research and development in terms of technical, economic, and social benefits. (1) Technical impacts: by establishing a replaceable and multifunctional modular swarm system, STCR technology will be rejuvenated due to substantial reduction of R&D costs. Based on open HPI and API of SMARTBEE system, the academia and industry will be able to develop end-effectors with various needed functions to catalyze the application of STCRs. (2) Economic impacts: through establishing a universal ICT platform, the repetitive R&D process of designing each STCR will be significantly reduced. The long-term benefits to post-industrial societies of adopting the SMARTBEE system will substantially outweigh the costs of implementing and operating the platform. (3) Social impacts: by implementing SMARTBEE system, labor shortage pressure caused by low birth rate in post-industrial societies will be soothed. Furthermore, human construction activities considered as difficult, dirty, and dangerous will be further substituted, thus reducing the potential healthcare expenditure caused by accidents in renovation industry.

**Conclusion & Further Research**

This paper has given an overview of the framework of SMARTBEE system (Single/Multi-task On-site Adaptable Renovation Robot Technology for Building Engineering Enhancement), and how the proposed system would overcome the challenges imposed on the renovation industry in the context of ageing society. The outcomes of SMARTBEE system will challenge the status quo of the STCRs application and thus will generate profound technical, economic, and social impacts. Admittedly, SMARTBEE is still at its conceptual stage, and it still requires further research, implementation and pilot project in the future to verify the effectiveness and practicality of the system. Specifically, in the future research, special attention needs to be paid on the following aspects. (1) Based on the proposed standardized modular connector, more modularized end-effectors with different functions, as well as more variety of modularized mobile bases and translational/rotary joints need to be developed and integrated into SMARTBEE system in the later research activities to enrich the library of the system. (2) A feasible collaboration between various STCRs within SMARTBEE system will be the key to the successful application of the proposed system. Therefore, developing controllers for the safe operation of modular robotic solutions as well as developing assistive haptic control and shared control architectures to support different levels of autonomy, and also realizing the integration of wearable haptics as human-machine-interface will be of primary importance to the system. (3) In order to promote user acceptance, the user interface must be user-friendly, and the process of the installation and the reconfiguration of the system must be uncomplicated and plug-and-play. (4) Safety issue must be thoroughly and rigorously considered, especially when human-robot interaction is involved. The ethics and privacy issue involving human-robot interaction must be rigorously discussed under the related laws and regulations in Germany and later in EU.

**References**


Simulation Mathematical Model of Mechatronic Sliding Formwork for Monolithic Tower with Variable Cross Section

Alexey Bulgakov¹, Tatiana Kruglova², Daheer Sayfeddine²

¹ South West State University, Kursk, Russia
² South Russian State Polytechnic University, Novocherkassk, Russia

* Corresponding author (a.bulgakow@gmx.de)

This paper describes mechatronic complex handling construction of monolithic towers. Sliding deck method expedites the construction of monolithic tower structures. Effective autonomous control of sliding shuttering can be achieved by developing adequate mathematical model of the controlled system taking into consideration external and internal influences on performing mechanisms. In light of the above, the context of this paper covers functional analysis of the technological operations of erection of monolithic structures, the development of the mathematical model, the structural organization of the mechatronic complex taking into consideration the variation of the diameter structure.

Keywords: Automation, Robotics, Construction, Mathematical Model, Monolithic Structures, Mechatronic Formwork

INTRODUCTION

One of the advantages of the sliding shuttering method is the possibility of implementing a continuous construction process. Unlike other types of formworks, construction approach on the basis of sliding method allows to automate the main stages of the process of erection of monolithic building. The technology of this method comprises continuously feeding and stacking concrete, installing reinforcement lifting formworks and regulating the control parameters [1-7]. Moreover, most of the described technological operations are carried out simultaneously.

During the construction of structures with variable cross-sections, and while the shuttering is lifted, the position of the indoor and outdoor shields overlaps. The automation process of the construction work of variable cross-section structures necessitate in providing synchronous repositioning of shields in accordance with special arrangements while lifting the formwork. For instance, adjusting the position error of the shuttering panels must not exceed 5 mm. In case of structures with variable wall thickness, the technology allows for independent variation in the position of internal and external formwork panels and a separate control for panels position. In this case, the deviation from the control tolerances should not exceed 2-3 mm.

In the following section, we outline the technological features of the construction of monolithic structures using sliding mechatronic complex automating several technological operations.

STRUCTURAL ORGANIZATION OF THE SLIDING MECHATRONIC COMPLEX

Firstly, the analysis of the erecting technology of monolithic structures shows that the integration of mechatronic system for concrete work should be carried out using sliding formwork method, which allows for continuous-cyclic process of concreting [8]. While designing the mechatronic system, it should be taken into account the varying radius, as this is the most common and complex version of structures, construction of which is associated with lots of operational adjustments, thus significant loss of time. Examples of structures with variable cross-sections can serve chimneys, television and observation towers with conical or hyperbolic cross-section.

Secondly, the erection of monolithic structures requires that the mechatronic system should perform concrete molding and sealing tasks. Therefore, the mechatronic complex should be equipped with robotic manipulators, executing simultaneously stacking of concrete, setting up and mounting the necessary reinforcements [9]. The block diagram of the construction robotic complex is shown in Fig. 1. The most difficult task is to automate shielding operation, which is divided into separate tasks. The suggested solution is to have two robots: the first is used to ensure the installation and fastening of the vertical reinforcement coming from the transport and storage device, while the latte executes tasks related to horizontal fittings supplied by a special wire-feeder. Each robot has its own control system.

The construction complex includes an informative-measuring system, which controls the position of the platform and formwork, processes of laying concrete and reinforcements. Planning process sequence and synchronization of different robotic systems is supervised by a higher-level control system. The sliding mechatronic complex should provide automatic lifting of the formwork during the concreting of the walls, automatic change of the radius of the formwork during the lifting, shuttering position adjustment in the event of displacement and torsion of the platforms.
Fig. 1. Structure of robotic technological complex for the construction of monolithic towers with variable cross-section

MATHEMATICAL MODEL OF THE SLIDING MECHATRONIC CONSTRUCTION SYSTEM WITH VARIABLE OPERATING RADIUS

During operational process, significant static and dynamic loads are applied on the lifting jacks of the formwork, which are characterized by uneven redistribution over time. When the platform is lifted, load change occurs due to the staking of concrete within the formwork shields at the start of movement, which, in its turn, breaches the synchronization of different mechanisms. This occurs as well during redistribution or changes in static loads applied to the formwork.

The mechatronic construction complex (MC) consists of a platform, which is mounted on an \( n \) numbers of electric lifting jacks (LJ), located on a circle of radius \( R_d \). Under the platform, the mechanisms of radial displacement are mounted with corresponding steps equal to radius \( R_M \). In addition, there are two reference systems: the tower body axis \( X_TY_TZ_T \) and the MC body axis \( X_MY_MZ_M \). We assume that at the start of the process, both of the axis systems coincide. The relation between the two reference systems is represented using the displacement vector \( \overline{X}_M \) and the rotation matrix \( A_M \). The displacement vector is related to the lifting jacks positions and it is calculated using the following equation:

\[
\overline{X}_M = [x_M, y_M, z_M]^T;
\]

Where

\[
x_M = \frac{1}{n} \sum_{i=1}^{n} x_L^{(i)}; \quad y_M = \frac{1}{n} \sum_{i=1}^{n} y_L^{(i)} \quad \text{and} \quad z_M = \frac{1}{n} \sum_{i=1}^{n} z_L^{(i)};
\]

Regarding the rotational matrix, it is convenient to express its elements in terms of rotational angles: the angle of inclination \( \alpha_M \), direction of inclination \( \beta_M \) and torsion of the platform \( \psi_M \), which in their turn are correlated with the coordinates of lifting mechanisms and platform center coordinates:

\[
\alpha_M = \arctan \left[ \max \left( \frac{\Delta z_L^{(i)}}{R_L} \right) \right];
\]

\[
\beta_M = \frac{2\pi}{n} \left( \max \left( z_L^{(i)} \right) \right);
\]

\[
\psi_M = \frac{1}{n} \sum_{i=1}^{n} \arctan \left( \frac{y_L^{(i)} - \sum y_L^{(i)}/n}{x_L^{(i)} - \sum x_L^{(i)}/n} \right) - \frac{2\pi}{n} (i - 1);
\]

To obtain \( A_M \), we have to rotate the reference system \( X_MY_MZ_M \) by \( \beta_M \) around the \( Z_T \). Then, we have to rotate the \( X_MY_MZ_M \) by \( \psi_M \) around \( Y_T \). The last step is the rotate \( X_MY_MZ_M \) by \( (\psi_M - \beta_M) \) until the axis \( X_T \) and \( X_M \) coincide. The result is shown in equation (3):
\[
A_M = A(\alpha_M) \cdot A(\beta_M) \cdot A(\psi_M) = \\
\begin{bmatrix}
\cos \beta_M & -\sin \beta_M & 0 \\
\sin \beta_M & \cos \beta_M & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos \alpha_M & 0 & \sin \alpha_M \\
0 & 1 & 0 \\
-\sin \alpha_M & 0 & \cos \alpha_M
\end{bmatrix}
\begin{bmatrix}
\cos(\psi_M - \beta_M) & -\sin(\psi_M - \beta_M) & 0 \\
\sin(\psi_M - \beta_M) & \cos(\psi_M - \beta_M) & 0 \\
0 & 0 & 1
\end{bmatrix}
\] (3)

In addition, we must include the kinematic relations, allowing determining the angles of rotation of \( \text{MC} \). Resolving the inverse kinematic problem leads to the following equalities:
\[
x_{ij}^{(0)} = [R_a^2 - (z_{ij}^{(0)})^2]^{1/2} \cos \left(\frac{2\pi}{n}(i - 1)\right);
\]
\[
y_{ij}^{(0)} = [R_a^2 - (z_{ij}^{(0)})^2]^{1/2} \sin \left(\frac{2\pi}{n}(i - 1)\right);
\]
\[
z_{ij}^{(0)} = R_a \sin \alpha_M \cos \left(\frac{2\pi}{n}(i - 1) - \psi_M - \beta_M\right).
\] (4)

During the operation, shields can be moved relatively from the platform center. Therefore, there is a need for determining the position of the center of the formwork, and estimating the deviation. The center position of the formwork in the coordinate system \( X_Y Z \) is calculated using the following equation:
\[
x_c = \sum_{j=1}^{m_i} R_{ij}^{(0)} \cos \left(\frac{2\pi}{n}(j - 1)\right) = \sum_{j=1}^{m_i} x_{ij}^{(0)};
\]
\[
y_c = \sum_{j=1}^{m_i} R_{ij}^{(0)} \sin \left(\frac{2\pi}{n}(j - 1)\right) = \sum_{j=1}^{m_i} y_{ij}^{(0)}.
\] (5)

Where \( R_{ij}^{(0)} \) is the suspension radius of \( j \)-formwork. Based on possible locations of the shields, we can determine the arithmetic mean of the formwork radius, which allows evaluating the deviation of the shields from the setup position. It is calculated as:
\[
R_{\text{mean}}^{(0)} = \frac{1}{n} \sum_{j=1}^{n} R_{ij}^{(0)}.
\] (6)

An important task to perform in order to develop the mathematical model of the complex is to determine the corrective parameters and calculation of estimated positions of the jacks. Therefore, the solution of the inverse problem is carried out based on the initial displacement center \( x_c^{(0)}, y_c^{(0)} \) and formwork radius \( R_{\text{mean}}^{(0)} \). In accordance with fig. 2, we can correlate the angular coordinates with the lifting jacks' locations and the shifted center of the formwork:
\[
x_{ij}^{(0)} = R_{ij}^{(0)} \cos \theta_j - R_{\text{mean}}^{(0)} \cos(\psi_j); \]
\[
y_{ij}^{(0)} = R_{ij}^{(0)} \sin \theta_j - R_{\text{mean}}^{(0)} \sin(\psi_j);
\] (7)

\[
\theta_j = \frac{2\pi}{n}(j - 1);
\]
\[
\theta_j^{(0)} = \theta_j - \arccos \left(\frac{x_{ij}^{(0)} \sin \theta_j - y_{ij}^{(0)} \cos \theta_j}{R_{ij}^{(0)}}\right).
\]

As a result of the equation (7), we obtain the expression for the formwork radius taking into account the coordinates of the shifted center from the center of the platform. Hence we can write:
\[
R_M^{(j)} = \sqrt{\left[R_M^{(0)} - \left(x_{ij}^{(0)}\right)^2 + \left(y_{ij}^{(0)}\right)^2\right] + \left(z_{ij}^{(0)}\right)^2};
\]
\[
r_M^{(j)} = R_{ij}^{(0)} \cos \theta_j + y_{ij}^{(0)} \sin \theta_j.
\] (8)

The current value of the radius \( R_M^{(j)} \) can be computed using the following equation:
\[
R_M^{(j)} = R_M^{(0)} + \triangle R_M^{(j)} + \Delta R_M^{(j)};
\] (9)

Where \( 
\Delta R_M^{(j)} \) - is the estimated change in the radius when climbing to a height \( h \).

Due to the fact that in the construction process, the formwork can moved with reference to the platform, it becomes necessary to describe the position of the formwork center with reference to the tower body-axis \( X_Y T Z_T \). If the position of the platform in the coordinate system \( X_Y T Z_T \) is characterized by the coordinates \( x_M^{(0)}, y_M^{(0)} \) and \( z_M^{(0)} \) and the position of the formwork is described using \( x_{ij}^{(T)}, y_{ij}^{(T)} \) and \( z_{ij}^{(T)} \), then the coordinates describing the position of the formwork in its own body-axis system can be found as follows:
\[
x_{ij}^{(T)} = x_{ij}^{(0)} + x_{ij}^{(c)} = x_{ij}^{(0)} + \sum_{j=1}^{n} R_{ij}^{(0)} \cos \left(\frac{2\pi}{n}(j - 1)\right);
\]
\[
y_{ij}^{(T)} = y_{ij}^{(0)} + y_{ij}^{(c)} = y_{ij}^{(0)} + \sum_{j=1}^{n} R_{ij}^{(0)} \sin \left(\frac{2\pi}{n}(j - 1)\right).
\] (10)

Where, \( x_{ij}^{(0)} \) and \( y_{ij}^{(0)} \) are the current coordinates describing the position of the lifting jacks.

While developing the model, it is necessary to include the equations that allow determining the angles \( \alpha_M \) and the direction of tilting platform \( \beta_M \) with reference to the controlled parameters \( x_M^{(0)}, y_M^{(0)}, z_M^{(0)}, z_L^{(1)} \), \( \varphi_T \), \( \alpha_M = \arctan \left(\frac{\max \Delta z_{Lj}^{(1)}}{R_{Lj}^{(1)}}\right) \); (11)

\[
\beta_M = \frac{2\pi}{n} \sqrt{\left(\max \Delta z_{Lj}^{(1)}\right)^2 + R_{Lj}^{(1)^2}}.
\]

Where, \( \Delta z_{Lj}^{(1)} \) - is the difference between \( z_L^{(1)} \) and \( z_M \).
The equation describing the deformation of the formwork is presented in equation (12):

\[
\Delta R_M^{(j)} = R_M^{(j)} - R_M = R_M^{(j)} - \sum_{m} \frac{R_m^{(j)}}{m};
\]

\[
\Delta \tau_{LJ}^{(j)} = R_M^{(j)} \sin \alpha_M . \cos \left( \frac{2\pi}{n} j - \beta_M \right);
\]

When tilting the platform at an angle \(\alpha_M\), during its lifting with a critical speed equals to \(\frac{\tau}{n}\), increases the tilting of the center coordinates with reference to the axis \(Z_T\). The projection of this increment with reference to the axis \(X_T\) and \(Y_T\) is described using the following equations:

\[
y_M = \sum_{i=1}^{n} y_{LJ}^{(i)} ;
\]

\[
\dot{x} = v_M \cos \alpha_M \cos \beta_M ;
\]

\[
\dot{y} = v_M \cos \alpha_M \sin \beta_M .
\]

Where, \(v_M\) — is underestimated as arithmetic mean of the velocity of the lifting jacks \(y_{LJ}^{(i)}\).

Taking into consideration the tilting angle of platform, its center deviates from the original axis. This deviation is expressed using the equation:

\[
\frac{\cos (\frac{2\pi}{n} i [\max(\Delta \tau_{LJ}^{(i)})])}{\max(\Delta \tau_{LJ}^{(i)})} = \sum_{i=1}^{n} \frac{y_{LJ}^{(i)}}{n} \cos \left( \arctan \left( \frac{\max(\Delta \tau_{LJ}^{(i)})}{R_M} \right) \right);
\]

\[
\sin \left( \frac{2\pi}{n} i [\max(\Delta \tau_{LJ}^{(i)})] \right);
\]

This abovementioned equation (14) allows us to describe the process of displacement of the platform when rising. This can be computed using the following equation:

\[
x_M(t) = \left( \int y_M dt \right) \cos \alpha_M \cos \beta_M ;
\]

\[
y_M(t) = \left( \int y_M dt \right) \cos \alpha_M \sin \beta_M .
\]

The above ratio must be supplemented by the equations, synchronizing the work of lifting and controlling mechanisms of \(MC\). To do this, we have to establish the dependence of the radius with reference the lifting height of the platform:

\[
R_M^{(a)} = R_M^{(a)} - z_M^{(a)}(k) + h_M(k) \cdot \tan \varphi_M = \] 

\[
= R_M^{(a)} - (z_M^{(a)}(k) + \int_{t_0}^{t} v_M dt) \cdot \tan \varphi_M ;
\]

Where, \(\varphi_M\) — is the tilting factor; \(z_M^{(a)}(k)\) — is the initial position of the platform at the k-step; \(h_M(k)\) — the movement of the platform at k-step and the sum \(z_M^{(a)}(k) + h_M(k)\) — represents the current height of the platform. In light of that the synchronization formula between the different mechanisms can be written as follows:

\[
r_M^{(a)}(t) = \int v_M dt \cdot \tan \varphi_M .
\]

The obtained relationship of lifting and control variables, which incorporates parameters of \(MC\) is shown as block diagram in Fig. 3. The output parameters are the coordinates of the center of the platform \(x_M\), \(y_M\) and \(z_M\), the mounting angle \(\alpha_M\), the direction of inclination \(\beta_M\), the radius of shields location \(R_M\), as well as the center coordinates of the formwork in different body-axis systems.

Since in the construction process, \(MC\) is exposed to a number of external and internal disturbances, the generation of transfer functions for different mechanisms should reflect their influence, thus to obtain adequate and realistic mathematical model of \(MC\).

For instance, the mechanical complex is installed under direct sunrays, which cause dilation of several components. As a consequence, this imposes variation in the design parameters. Let us assume that \(\Delta x_T\), \(\Delta y_T\) and \(\Delta \alpha_T\) are the parameters deviation of \(MC\) platform from the designed body-axis system and from the designed tilting angle respectively. These parameters are determined by the temperature coefficient of linear expansion of the tower height \(\varepsilon_t\), the temperature difference between sunny and shady sides \(\Delta \tau\) and the direction of the solar energy flow \(\theta_\tau\). Hence we can write:

\[
K_T = \frac{H \cdot \varepsilon_t}{4\pi \cdot R_T} ;
\]

\[
\Delta x_T = 0.5K_T \cdot H \cdot \Delta \tau \cdot \cos \theta_\tau ;
\]

\[
\Delta y_T = 0.5K_T \cdot H \cdot \Delta \tau \cdot \sin \theta_\tau ;
\]

\[
\Delta \alpha_T = K_T \cdot \Delta \tau .
\]

Where, \(H\) — is the height of the tower and \(K_T\) — is the deformation coefficient.

While simulating the thermal effects, we need to take into account the inertia of the heating process, which is described by an aperiodic element introduced into the model. The influence of wind load also causes a shift in the values of the platform setups designated as \(\Delta x_w\), \(\Delta y_w\) and \(\Delta \alpha_w\). These deviations are calculated in equation (19):

\[
\Delta x_w = K_w \cdot R_w \cdot \cos \theta_w ;
\]

\[
\Delta y_w = K_w \cdot R_w \cdot \sin \theta_w ;
\]

\[
\Delta \alpha_w = K_w \cdot R_w .
\]

Where, \(K_w\) — is the deformation coefficient caused by the wind.

The deviation and slope of the formwork caused by unilateral action of the solar heat and wind load are represented using transfer functions equations:
\[ W_t(p) = W_t^{(\lambda)}(p) + W_t^{(\xi)}(p) = \left( \frac{K_t^H(H) + K_t^E(H)}{p} \right) \left( \frac{1}{T_{rp} + 1} \right) \]

\[ W_v(p) = W_v^{(\lambda)}(p) + W_v^{(\xi)}(p) = \left( \frac{K_v^H(H) + K_v^E(H)}{p} \right) \left( \frac{1}{T_{vp} + 1} \right) \]

\[ \text{Fig 3. Block diagram of the mechatronic construction complex} \]

Where, \( W_t(p) \) and \( W_v(p) \) — are the transfer functions of the offset and slop \( W_t^{(\lambda)}(p) \) and \( W_v^{(\lambda)}(p) \) — are the transfer functions of the linear deviation caused by the solar heat and wind load; \( W_t^{(\xi)}(p) \) and \( W_v^{(\xi)}(p) \) — are the slop transfer functions of the angular deviation caused by the solar heat and wind load and \( p \) — is the Laplace operator.

To describe the static load effect on the lifting jacks and its reflection on the platform, we introduce new matrix \( D_S \), the elements of which characterize the distribution of the load, depending on its position on the platform. As a result of multiplying the static load vector \( \mathbf{Q}_S \) by matrix \( D_S \), we obtain the load vector of the lifting jacks \( \mathbf{Q}_{LP} \), whose elements are the value of the static load acting on the corresponding jack. The effect of static loads on the lifting jacks formwork is an inertial astatic second-order process, described by the following transfer function:

\[ W_S(p) = \frac{K_S}{p^2(T_{sp} + 1)} \] (21)

As it was already mentioned, in the process of lifting the platform, possible deformation of its radial beams can occur, which leads to the appearance of elastic forces, providing additional load on the lifting jacks. To reflect this phenomenon in the model, we will introduce the matrix of stiffness \( \mathbf{C}_{def} \), which is calculated on the basis of the elastic force vector \( \mathbf{F}_{def} \):

\[ \mathbf{F}_{def} = \mathbf{C}_{def}(\mathbf{x}_L - \mathbf{z}_L) \]

When modeling the mechanisms of radial movement, we have to take into account the friction force in the screw pair \( F_{sp} \), concrete reaction \( F_{CR} \), as well as the effect of the elastic forces of the formwork \( F_E \). These factors have an inertial character, which can be characterized by time constants \( T_{sp} \), \( T_{CP} \) and \( T_E \) respectively. Hence, the transfer functions of the external forces can be computed as follows:

\[ W_{sp}(p) = \frac{K_{sp}}{p(T_{sp} + 1)} \]

\[ W_{CR}(p) = \frac{K_{CR}}{T_{CR}} \]

\[ W_E(p) = \frac{p(T_{sp} + 1)}{p(T_{FE} + 1)} \] (23)

The violation of the synchronization between different mechanism leads to a gradual increase in the force of concrete reaction \( F_{CR} \), the variation of which is represented in the following system:

\[ F_{CR} = F_{CR}^0 + K_p \Delta r_M - \Delta r_M \leq \Delta r_M \leq \Delta r_M^0 \] (24)

Where, \( K_p \) — is the coefficient representing the concrete pressure on the shields, \( \Delta r_M \) — is the radial deviation of the shields and \( F_{CR}^0 \) — is the initial force of the concrete on the shields.
Conclusion
The analysis of kinematic and dynamic properties of the mechatronic complex and disturbances are represented in the complete block diagram shown in Fig. 4. This allows for better analysis of dynamic characteristics, to predict the deviation of positioning of formwork during lifting and to investigate the influence of the disturbances on the performance of the mechatronic complex.

References
Inverse Kinematics for Teleoperated Construction Machines: a Novel User-oriented Approach

Matteo Ragaglia¹*, Alfredo Argiolas¹, and Marta Niccolini¹

¹ Yanmar Research & Development Europe, Viale Galileo 3/A, 50125 Florence (Italy)
* Corresponding author (matteo_ragaglia@yanmar.com)

Abstract: This paper presents a novel approach to the problem of inverse kinematics for teleoperated robots. As a matter of fact, whenever the operator brings the manipulator near kinematic singularities or near the boundaries of its workspace, it is necessary to adapt the solution of the inverse kinematics problem in order to: keep the manipulator as closest as possible with respect to the human operator command, guarantee smooth robot motion, produce smooth joint saturations. Moreover, in case of kinematic redundancy, the algorithm should take advantage of the extra DoFs in order to obtain the aforementioned goals. Starting from a previously published solution to the problem of approximated inverse kinematics, some improvements have been introduced and comparative evaluation has been performed.

Keywords: Construction Machines, Teleoperation, Inverse Kinematics, Kinematic Singularities, Joint Saturations

INTRODUCTION
Nowadays, teleoperated (i.e. remotely operated) robots are experiencing a growing success in various application domains: military, search and rescue, disaster recovery, etc. Nevertheless, as far as the construction industry is concerned, robotic technologies have not become very popular yet. As a result, various operations that require high power and high accuracy (such as panel positioning, plumbing, material handling) are still manually performed by human workers in very inefficient and dangerous ways. After a thorough field investigation, we believe that the construction field could definitely benefit from the introduction of teleoperated robots in terms of both productivity and human workers’ safety.

During teleoperation, a human operator remotely controls the manipulator by sending commands to some sort of Human-Machine Interface (HMI). If the interface consists in a scaled version of the robot, it is possible to implement teleoperation directly in the joint space. Not only this solution lacks generality, but also it cannot be easily adapted to manipulators characterized by different kinematic chains. Consequently, in general, the HMI is not kinematically similar with respect to the manipulator, thus entailing the need to implement Inverse Kinematics (IK) in order to translate into the joint space the commands produced by the operator in the task space (see Fig. 1).

Moreover, considering a teleoperation scenario, three main problems must be addressed at the IK level:

- **kinematic singularities**: in case the operator brings the robot near internal singularities (i.e. singularities located inside the robot’s workspace), the IK algorithm should not produce large values for joint velocities;
- **joint limits**: in case the operator brings the robot to its workspace limits (i.e. external singularities), the IK algorithm should keep the machine inside the workspace, while producing a smooth and intuitive trajectory;
- **redundancy resolution strategy**: if the robot is equipped with seven or more DoFs, the IK algorithm should decide when and how to exploit the extra-DoFs. For instance, the algorithm could exploit the kinematic redundancy in order to maximize manipulability.

In this work, a novel strategy for the calculation of IK in teleoperation scenarios is presented. The proposed approach combines singularity avoidance, smooth saturations near joint limits and redundancy resolution. State of the art techniques are exploited to guarantee smooth trajectories in proximity of both internal and external singularities. On the other hand, gain scheduling procedures are introduced in order to activate (deactivate) task space error compensation and redundancy resolution in case the manipulator is far (near) from joint limits. In this way it is possible to generate smooth trajectories, while keeping the manipulator inside its workspace and trying to follow the operator’s command as much as possible.

![Fig.1. Teleoperation control scheme with IK stage.](image)

STATE OF THE ART
Considering a general manipulator, Direct Kinematics (DK) can be expressed as:

\[
\begin{align*}
\mathbf{x}_d & \rightarrow \delta \mathbf{x} \\
\mathbf{q} & \rightarrow \delta \mathbf{q}_k \\
\mathbf{T} & \rightarrow \delta \mathbf{T} \\
\mathbf{q} & \rightarrow \delta \mathbf{q}_f
\end{align*}
\]

\[
\mathbf{x} = \text{Forward Kinematics}
\]

\[
\begin{align*}
\delta \mathbf{x} & = \text{Inverse Kinematics} \\
\delta \mathbf{q}_k & = \text{Joint Servomotors} \\
\delta \mathbf{T} & = \text{Manipulator} \\
\delta \mathbf{q}_f & = \text{Forward Kinematics}
\end{align*}
\]
\[ f(q) \]

Given this formulation, the most simple approach to the IK:

\[ \frac{dx}{dq} = \left( \frac{df(q)}{dq} \right) q = f(q) \dot{q} \quad (2a) \]

\[ \dot{q} = f^{-1}(q) \dot{x} \quad (2b) \]

\[ q \leftarrow q + \Delta t \dot{q} \quad (2c) \]

A typical problem that arises when dealing with differential kinematics inversion is represented by singularities, especially the internal ones. As a matter of fact, whenever the Jacobian matrix \( f(q) \) is rank-deficient, its inversion (or pseudo-inversion, in case of redundant manipulators) will produce enormous joint velocities \( \dot{q} \) even in presence of small task-space velocities \( \dot{x} \). In order to avoid this kind of situation, Damped Least-Squares (DLS) pseudo-inversion of the Jacobian matrix has been originally proposed by Wampler\(^1\) and further extended in various more recent contributions\(^2\). DLS pseudo-inversion is simply obtained by adding a perturbation term to matrix \( f(q) f^T(q) \) before inversion:

\[ f^T(q) = f^T(q) \left( f(q) f^T(q) + \alpha^2 I \right)^{-1}, \quad \alpha > 0 \quad (3) \]

Alternative approaches utilize redundancy to avoid rank-deficient configurations\(^3,4\), but in this case it is not possible to exploit kinematic redundancy for other purposes, like for instance increasing manipulability/dexterity during task execution or teleoperation. Strategies based on switching between different Jacobian matrices have also been proposed\(^5\), but all these approaches introduce the non-trivial problem of ensuring the continuity of motion during switching. Beside singularity avoidance, another relevant problem that may arise during teleoperation is represented by joint limits. If the operator generates unreachable commands (i.e. tries to bring the robot outside its workspace boundaries), one joint or more may not be able to achieve the required velocities, thus resulting in large task space errors. Differently from conventional robotic scenarios (where the joint limit problem is tackled at the path planning level), during teleoperation the human operator generates unpredictable commands, thus preventing the robot controller to completely avoid unreachable configurations.

Several solutions to the joint limit problem have been proposed in robotics literature. For instance, Chan and Dubey\(^6\) propose an approach based on redundancy resolution. Unfortunately methods like this work as long as the weighted Jacobian does not lose full rank. At that point redundancy can no longer be employed and the operator may bring the robot outside its workspace limits.

A very interesting approach that deals with both singularity avoidance and joint limits has been proposed by Schinstock\(^7\). The standard DLS approach is extended to include individual, dynamic weights on each of the joint variables. A more recent solution to the IK problem in presence of joint limits and redundant kinematics is represented by the Saturation in the Null Space technique\(^8\).

Unfortunately, while being quite elegant, this solution consists in an iterative algorithm that could be difficult to solve in real-time on embedded PCs/controllers.

Finally, several IK approaches have been proposed for the case of humanoid robots\(^9\) or human-like manipulators\(^10,11\), but the main focus of these solutions is on redundancy resolution (and eventually on self-collision avoidance), rather than on the aforementioned problems that affect teleoperation.

**PROPOSED ALGORITHM**

In order to provide better performances during teleoperation, an Inverse Kinematics algorithm has been designed, starting from Schinstock’s method\(^7\). This algorithm has been originally developed for teleoperation purposes and deals with both singularities and joint limits. It extends the weighted DLS strategy\(^1\) by dynamically weighting each joint contribution when a joint limit is approached. This way, the algorithm provides approximate solutions in the task space when the commands are not reachable, while still providing exact solutions inside the dexterous workspace.

**Modified Schinstock’s Algorithm**

Schinstock’s algorithm has been implemented and extended by integrating a Cartesian error compensation term (in terms of position and orientation) and a redundancy resolution strategy that tries to maximize the manipulability during task execution. Given the joint space weight matrix \( W_q(q) \) (positive definite) and the damping parameter \( \alpha(q) \), the next kinematic configuration is computed according to equations (4). For conciseness, explicit dependence of \( J, W_q \) and \( \alpha \) from \( q \) will be omitted from now on.

\[ J_w = W_q J W_q(q) \quad (4a) \]

\[ J_w^{-1} = J_w^T (J_w J_w^T + \alpha(q)^2 I_n)^{-1} \quad (4b) \]

\[ w(q) = \frac{1}{2n} \sum_{i=1}^{n} \frac{q_i - q_{i0}}{q_{i0} - q_{i0}} \quad (4c) \]

\[ q_i = q_0 \left( \frac{\partial w(q_i)}{\partial q_i} \right)^T \quad (4d) \]

\[ q = W_q(q) \left[ J_w^T W_x \left( \dot{q} + k_x e \right) + (I_n - J_f) \dot{q}_o \right] \quad (4e) \]

\[ q \leftarrow \min( q_M, \max( q_m, q + \Delta t \dot{q}) ) \quad (4f) \]

where:

- \( J \) and \( J_f \) are the Jacobian matrix and its Moore-Penrose pseudo-inverse, respectively;
- \( J_w \) and \( J_w^{-1} \) are the weighted Jacobian matrix and its Moore-Penrose pseudo-inverse, respectively;
• $W_k$ is the fixed task space weight matrix (positive definite);
• $n$ is the number of DoF of the robot;
• $I_n$ is the identity matrix of dimension equal to $n$;
• $x_d$ is the desired Cartesian speed;
• $e$ is the Cartesian position/orientation error;
• $k_1$ and $k_2$ are two fixed gains;
• $w(q)$ is the cost function that is minimized in order to solve the kinematic redundancy;
• $q_0$ is the null-space velocity term resulting from the minimization of $w(q)$;
• $q_M$ is the vector containing the maximum joint values and $q_m$ represents its $i$-th component;
• $q_m$ is the vector containing the maximum joint values and $q_{im}$ represents its $i$-th component;
• $\bar{q}_i$ is the $i$-th joint value at the mid of the course.

The explicit saturation, equation (4f), has been introduced in order to guarantee that joint limits are always satisfied. As a matter of fact, Schinstock’s algorithm decreases joint velocities in proximity of joint limits, but it may allow joint angles to overcome their upper and lower bounds.

Gain Scheduling Procedure

The introduction of the Cartesian error compensation and of the redundancy resolution strategy entails a non-trivial problem. For example, once a joint reaches its boundaries, the Cartesian error undergoes a significant increase, thus determining a huge velocity command that the robot cannot follow. On the other hand, also the redundancy resolution strategy must be deactivated in case of joint saturations, since the null-space velocity $q_0$ affects the task given that the robot loses its extra DoFs. In order to overcome this issue, a linear scaling procedure has been adopted. At first, the minimum distance between the joint angles and the corresponding boundaries is determined:

$$q_{d,min} = \min_i \min (q_{im} - q_i, q_i - q_{imin})$$

then, the gain parameters $k_1$ and $k_0$ are updated according to the pseudocode displayed in Fig. 2.

More in depth, these scaling procedures are based on the following parameters:

- $k_0^M (k_1^M)$ is the maximum value of gain $k_0 (k_1)$;
- $q_{k_0}^m$ and $q_{k_1}^M$ ($q_{k_1}^m$ and $q_{k_1}^M$) define a band inside which gain $k_0 (k_1)$ is scaled.

SIMULATION AND EXPERIMENTS

In order to validate the inverse kinematics algorithm previously described, we consider the following scenario: the Future Working Machine (FWM) prototype (a 8 DoF redundant robot shown in Fig.3) is given a velocity command in the task space in the form of different square waves along the Z-axis. In the first simulation, the robot is solicited with a square wave of amplitude equal to 0.025 m/s and period equal to 50 s.

The following plots show that, in absence of joint saturations, our algorithm gives the same results with respect to the standard weighted DLS pseudo-inverse algorithm in terms of Cartesian position (Figure 4), Cartesian position error (Figure 5), and joint positions (Figure 6).

**Algorithm 1** $k_1$ gain scheduling algorithm:

1. if $q_{d,min} > q_{k_1}^M$ then
2. \( k_1 = k_1^M \)
3. else
4. if $q_{k_1}^m \leq q_{d,min} \leq q_{k_1}^M$ then
5. \( k_1 = \frac{(k_1^M - k_1^m) (q_{d,min} - q_{k_1}^m)}{(q_{k_1}^M - q_{k_1}^m)} \)
6. else
7. \( k_1 = 0 \)
8. end if
9. end if

**Algorithm 2** $k_0$ gain scheduling algorithm:

1. if $q_{d,min} > q_{k_0}^M$ then
2. \( k_0 = k_0^M \)
3. else
4. if $q_{k_0}^m \leq q_{d,min} \leq q_{k_0}^M$ then
5. \( k_0 = \frac{(k_0^M - k_0^m) (q_{d,min} - q_{k_0}^m)}{(q_{k_0}^M - q_{k_0}^m)} \)
6. else
7. \( k_0 = 0 \)
8. end if
9. end if

In a second simulation, the robot is solicited with a square wave of amplitude of 0.100 m/s and the same period of 50 s. In this case, multiple robot joints reach their saturations and the proposed inverse kinematics algorithm clearly outperforms the standard weighted DLS pseudo-inverse algorithm in terms of Cartesian position (Figure 7), Cartesian position error (Figure 8) and joint positions (Figure 9).

Moreover, Figure 10 shows that the saturation of joint #3 is much more smooth when the proposed algorithm is used instead of the standard pseudo-
inverse one (that enforces a with direct joint saturation).

Figure 11 and Figure 12 show the robot configuration enforced by the two algorithms at time equal to 25 s (i.e. when the commanded task-space position is furthest from the robot's workspace limits). The representations have been realized using Matlab Robotics Toolbox\textsuperscript{12}. It is worth noting that the proposed algorithm is able to keep the manipulator as near as possible to the commanded task-space position even in case of multiple joint saturations.

Finally, Figure 13 shows the reason we introduced the gain scaling procedures previously described. In presence of joint saturations, in fact, the gain scheduling procedure allows to avoid oscillations and very large spikes on joint velocities, thus entailing more accurate positioning and less stress on the mechanical structure of the robot.

**CONCLUSIONS AND FUTURE DEVELOPMENTS**

In this paper a novel procedure for the calculation of inverse kinematics in teleoperation scenarios is presented. The proposed approach ensures singularity avoidance and guarantees smooth saturations near joint limits. Moreover, this algorithm is able to effectively exploit kinematic redundancy. Several simulations have been performed to prove the effectiveness of our approach. Given the collected results we can state that whenever the commanded trajectory does not exceed the robot workspace our algorithm guarantees the same tracking performances with respect to state of the art alternatives\textsuperscript{1-7}.
Fig. 7. Simulation #2 - Cartesian Position: reference (solid black), pseudoinverse (dashed dark grey), proposed algorithm (dashed light grey).

Fig. 8. Simulation #2 - Cartesian Position Error: pseudo-inverse (black), proposed algorithm (grey).

Fig. 9. Simulation #2 - Joint Positions: joint limits (solid black), pseudo-inverse (dashed dark grey), proposed algorithm (dashed light grey).

Fig. 10. Simulation #2 - Detail of Joint 3 saturation: joint lower limit (dashed black), pseudo-inverse (solid dark grey), proposed algorithm (solid light grey).

Fig. 11. Simulation #2 - Robot configuration at time equal to 25 sec with pseudo-inverse algorithm.
Fig. 12. Simulation #2 - Robot configuration at time equal to 25 sec with proposed algorithm

Fig. 13. Simulation #2 - Joint velocities: Schinstock’s algorithm (solid black), proposed algorithm (solid grey)

References
Automated refurbishment & end-of-life processes – research approaches in German and Japanese construction

Elisa Lublasser¹*, Kepa Iturralde², Thomas Linner², Sigrid Brell Cokcan¹ and Thomas Bock²

¹ Chair for Individualized Production in Architecture, RWTH Aachen University, Germany
² Chair of Building Realization and Robotics, Technische Universität München, Germany
* Corresponding author (lublasser@ip.rwth-aachen.de)

Recently, efficiency in the building fabrication process and on construction sites in terms of energy consumption, sustainability and reuse has become more and more important in the discussion of the building life-cycle and the construction site of the future. In this paper, different approaches for the development of automated refurbishment and end-of-life concepts with focus on robotic deconstruction within the construction sector will be introduced. Whereas RWTH Aachen is researching on the integration of industrial robots in the context of smart building automation and the digitalization of the construction site, TU Munich is researching concepts beyond industrial robots and prefabrication as one solution for preplanned deconstruction. An overview of the proposed concepts and the pros and cons of the various methods will be discussed in this paper.

Keywords: Automation; Robotics; Deconstruction; End-of-life; Refurbishment; Prefabrication; robot motion programming

INTRODUCTION
As a basis for the detailed development of automated processes, the following introductory section describes the demand for new refurbishment and end-of-life processes to locate the research aims within a global context.

General demand for new refurbishment & end-of-life processes
Generally, the demand for refurbishment and deconstruction of whole buildings as well as building parts is drastically increasing¹ due to rising vacancy rates and worsening building conditions of the building stock among other criteria. Furthermore, in the past years major changes in society that have modified the requirements of residential architecture have been observed. To meet the new standards while preserving existing built resources, the building stock has to be generally reorganized including the partial and locally defined deconstruction of internal and external building parts such as walls, slabs and facades. In addition, the increasing scarcity and cost increase of resources lead to the demand for future refurbishment and end-of-life approaches for buildings which ensure that the material bound in the building can almost fully be recovered for reuse either within the given building or for other construction projects. This recovering is, however, labor intensive, involves highly repetitive processes, and in some cases is dangerous for human beings. The utilization of robots in this filed is thus imperative.

Moreover, not only the demolition sector but also the construction industry have become more and more affected by intensified recycling and reuse standards such as the Waste Framework Directive (WFD) of the European Union or the German Kreislaufwirtschaftsgesetz (KrWG). Therefore, the building industry is in need of recycling and deconstruction strategies for recent construction setups which often include more complex and intertwined composite elements than in past years due to their highly optimized function based layer arrangement. One example for these elements are external thermal composite systems (ETICS). The acceptance and future application of such system are strongly related to reliable recycling strategies supporting the KrWG regulations but are not yet fully examined.

Although the processing of great amounts of construction and demolition waste (C&D) already reaches a high degree of recycling², there is still great potential for high quality element reuse of certain building elements. Therefore, the current deconstruction processes have to be adapted to be able to provide the necessary varietal purity for the pursued element reuse.

All in all, new refurbishment and deconstruction processes have to be developed to be able to not only cope with the described circumstances but also efficiently handle the deconstruction and refurbishment in high-wage countries. The efficiency has to influence the process development to optimize working efforts, working time and costs to guarantee the competitiveness of construction and demolition com-
panies. Concurrently, the working conditions within the process have to be increased while decreasing emission for the working as well as living environment close to or at building and demolition sites to provide safer and more attractive jobs for workers in the building and demolition sector to match the changing requests of the labor market.

STATE OF THE ART DECONSTRUCTION
Considering that future refurbishment and end-of-life approaches for buildings can be characterized rather as systemized building deconstruction (which allows for component-reuse and recycling) than as building demolishing, the actual process can be subdivided into three major phases, namely the preparation of deconstruction, deconstruction and material separation, and the processing of deconstructed components. The development of automation strategies and robotic technology for all three phases that allow to treat a building as a modular product which can be systematically disassembled increasingly is a topic in R&D in both industry and academia. Currently, deconstruction takes place at different levels of automation, material separation, manual labor integration and costs. While the application of frequently used hydraulic excavators (HE) with various attached deconstruction equipment offers a fairly automated, time and cost efficient process, it is not able to support the pursued optimization of deconstruction and refurbishment processes with a high quality separation for material reuse. So far, this is only possible with a great amount of manual labor cooperation because the big machinery lacks of necessary local accuracy. On the other hand, manual demolition work with the support of small machinery such as pneumatic hammers is a rather slow process which is often mentioned as indicator for cost-driving positions of demolition services. Considering also the working conditions, manual demolition procedures entail more disadvantages which are otherwise mostly prevented by the protection of the HE cabin:

1. direct exposure to dust, equipment vibrations and unpredictable hazardous situation through uncalculatable material fall off
2. direct contact to unexpectedly exposed contaminated materials
3. physical stress because of equipment payload and manual material transportation

However, manual deconstruction is so far the most effective procedure for high quality material separation on site. The human dexterity as well as immediate intuitive adaption of working procedures and adequate tools allow for all degrees of purity of variety of harvested materials and thus allow for controlled and predictable material and building element reuse.

In conclusion, common deconstruction procedures are not yet applicable for optimized refurbishment processes. New approaches have to be developed combining the advantages of various common procedures.

NEW APPROACHES FOR AUTOMATED REFURBISHMENT & END-OF-LIFE PROCESSES
In the following sections, the two different research approaches for the optimization of refurbishment and end-of-life processes overcoming the discrepancies of common procedures as described above are explained in detail.

Prefabrication and deconstruction
This section summarizes the research developed by the Chair for Building Realization and Robotics at TU Munich on necessary frameworks and systems for the automated refurbishment and end-of-life processes based on results of prefabrication research in construction. The research aims and results are accompanied by preliminary research and industry examples of the Japanese sector of automation and robotics in construction.

Holistic approach & sub-systems
Achieving an optimal building stock is a goal of the European Union. For that purpose, there have been several publicly financed projects that have been working with several solutions in order to ameliorate traditional ways of gathering a holistic building renovation. An automated and robotic building refurbishment process will facilitate the renovation and maintenance of the building stock. For conceiving a system for robotic building renovation, three main concepts of three main sub-systems have to be considered:

1. Sub-System 1. Adaptable module or element configuration. The bespoke added element or module is adapted to the geometry and physics of the existing building.
2. Sub-System 2. Robotic manufacturing process of customized elements or modules. This concept leads to flexible or lean manufacturing.
3. Sub-System 3. Robotic installation process of modules or elements that are placed and fixed onto the existing building. To achieve that purpose, there must be a redevelopment of existing robotic and non-robotic hardware and software tools which then have to be reconceived for building refurbishment.
Under these three main sub-systems, a hierarchized and interrelated chart of sub-sub-systems must be organized. Since the System can grow in complexity, methods such as Axiomatic Design or TRIZ are always necessary. E.g. focusing on Sub-System 2 (see Figure 1), the primary goal is to improve the off-site manufacturing process. Other goals can also be pointed out, such as:

1. Adapt to different degrees of automation
2. Adapt to various assembly processes configurations depending on the module or element variations
3. Adapt to factory reconfigurations
4. Adapt to various supplying systems.

*Figure 1. Sub-System 2: Robotic manufacturing system for building refurbishment, a scheme*

As it can be observed, the issue of robotic building renovation is complex and needs a holistic vision in order to successfully achieve the goal.

**Related robotic technology for construction**

Specific and dedicated single task robots (Figure 2) have already been conceived to work in the interior and exterior of construction sites. Those robots operate different tasks such as dismantling the actual building elements and installing new ones.

*Figure 2. a) Interior Inspection Robot Shinyo Corporation Robot or Fujita Robot b) Interior Refurbishing Robot TB., c) Fig.3. Interior Refurbishing Robot Komatsu (All Copyrights by Thomas Bock, TU Munich)*

These technologies, in principle, need to be adjusted for being applied within the building refurbishment process.

**Preliminary examples for rapid refurbishment**

One of the best preliminary examples of rapid building refurbishment is the upgrading of the OMM building in Osaka in 1987. It was led by Takenaka Contractor Company and the YKK curtain wall manufacturer and installer. The main goal of the project was to add a second envelope layer in order to improve the thermal performance of the building. In this case, some relevant characteristics can be found:

1. Accurate measurement of the existing building envelope.
2. Accurate positioning of connectors.
3. Accurate fabrication of bespoke curtain wall prefab modules.
4. Fast placement system of the new curtain wall using embedded rails
5. Rapid clamping, fitting and fixing mechanisms.

Although the construction industry of that time period in Japan was highly robotized, the used tools were actuated manually in this project. This shows that working in existing buildings due to the unstructured and poorly documented environment is more complex and requires more specific development.

**Large scale kinematics for construction and deconstruction**

Members of the Building Realization and Robotics Chair at TU Munich have approached a robotic system that is suitable for the installation of flat modules onto facades in order to improve the energetic performance of the building. This early stage research has focused on two main issues:

1. Development of robotic support bodies.
2. Design of the end-effector system defined as a Modular End-Effector (MEE) System.

Depending on the building typology, some support bodies adapt better to a given building situation. For instance, a support body based on Aerial Work Platform is more suitable for low rise buildings, whereas a Cable Driven robot would be appropriate for a high rise building. Figure 3 a) depicts a connector fixation process with an Aerial Work platform. In this case the MEE is performed semi-automatically and the operator can guide the whole process close to the task. On Figure 3 b) the MEE is used by an Automated Vertical Bridge crane. It can be observed that the MEE elevates the facade component. As shown in Figure 3 c), it has also been considered the choice of using the MEE as a cable suspended device by a cable robot.
The MEE system has been simulated using specific software. The simulation has focused on:

1. Structural behavior of the proposed MEE
2. Operability performance of the MEE system.

For the installation of the modules, the MEE needs to perform several tasks: drilling the existing wall, inserting the connector and placing the fixing and the module itself.

**On-site operation site factories**

Automated and robot supported deconstruction of buildings is accomplished by on-site operation site factories which are installed on the site as a cover basically move down the building coordinated by the deconstruction time schedule and allow the installation and operation of all sorts of robots and assistive tools. Thereby, a controlled, structured and systemized work environment is created on site. Bock and Linner sub-classified on-site approaches for systemized-deconstruction into three categories

<table>
<thead>
<tr>
<th>Typology 1</th>
<th>Typology 2</th>
<th>Typology 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed Sky Factory Supported by Building (moving downwards)</td>
<td>Open Sky Factory Supported by Building (moving downwards)</td>
<td>Ground Factory (fixed place) and Building Lowering</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Systems: Hat Down (Takenaka)</th>
<th>Systems: MoveHat (Nishimatsu)</th>
<th>Systems: DARUMA (Kajima)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TECOREP (Taisei)</td>
<td>RCM (Shimizu)</td>
<td>QB Cut-off (Obayashi)</td>
</tr>
</tbody>
</table>

The processing of lower level components, monomaterial parts or raw materials can be efficiently accomplished in off-site factories providing a structured environment for the use of automation and robotic technology. A more extensive example was developed by the Japanese housing manufacturer Sekisui Heim (Figure 5). They offer as part of their construction system a house reuse program where steel cells and frames that have been disassembled from an old house are “re-personalized” on their production lines and used for a new, individual building.

---

Table 1 Categorization of on-site deconstruction approaches employing robotic technology

For example, all six major Japanese contractors have developed systems for systemized and at least partly automated/robotic disassembly since 2008. One example is the HAT-Down system by Takenaka Corporation/T. Bock (Figure 4). In such on-site factories, the high-level components are disassembled (e.g. from top to bottom), then the harvested components are further process, for example, in a ground factory on-site into sub-assemblies and parts, which can then be handed over to off-site factories for recycling and reuse.

---

Figure 3. Automated façade element assembly with a) Aerial Work Platform b) Automated Vertical Bridge c) cable suspended robot. (Image: Iturralde, Linner and Bock, Chair for Building Realization and Robotics, Technische Universität München)

Figure 4. Automated building disassembly for urban mining (Image: HAT-Down system by Takenaka Corporation/T. Bock)

Figure 5. Large-scale deployment of sustainable buildings through advanced prefabrication (Image: Sekisui Heim)
Robotic arms for life-cycle oriented material and element refurbishment

The chair for Individualized Production in Architecture (IP) at RWTH Aachen University is currently researching on robot assisted deconstruction and refurbishment processes for the recovery of building material with a high degree of material separation as well as element reuse. The pursued application scenario of the new processes is based on the refurbishment of wall-construction based buildings especially supporting product recycling for reuse in the building industry\textsuperscript{15}. To be more precise, locally restricted and partially executed deconstruction of building elements and relocation of harvested reusable materials or building parts on the same building site within a new context will be sought, which can be referred to as a life-cycle oriented material and element refurbishment.

To quickly and efficiently achieve this ambitious goal, the interdisciplinary team of IP is researching on the implementation of well-known industrial robotic arms. The motivation here is to use standardized and reliable hardware to be able to focus the research on detailed software problems such as new task programming as well as human-machine interaction to guarantee a successful implementation in the so far poorly automated construction sector.

Figure 6. depicts an example of initial experiments on robotic arm assistance in the deconstruction process. Here, the robotic arm was programmed for precise stemming of masonry joints as preparation for a refurbishment process including the partial deconstruction of an external wall to gain a new opening and reusing of the harvested bricks for a new internal wall element while recycling other parts.

Advantages of robotic arm assistance

It is expected that the integration of robotic arms in the deconstruction process will be able to bridge the gap between common procedures combining their advantages. While relieving demolition and construction workers from the heavy equipment weight and direct exposure to hazardous situations\textsuperscript{16}, robotic arms are capable of controllable and precise movement, demolition and handling tasks to allow for direct element reuse without the necessity of major post-processing work. The so harvested material can then directly be reused on site in accordance to the refurbishment design. Thereby, the new process not only bridges the gap between different available machineries but also between the different architecturally and resource relevant tasks within a refurbishment project from demolition to construction in a de facto closed loop (see also section 0). Achieving this helps to reduce the consumption of energy and primary resources for construction tasks during refurbishment, since the manufacturing and transportation of new materials becomes superfluous.

Problems of robotic arm assistance

At the moment, standard industrial robotic arms can hardly be used freely for partial refurbishment of residential or public buildings because of their heavy weight, which is necessary to handle the heavy deconstruction equipment. Using large robotic arms endangers structural stability of common building construction. Furthermore, accessibility of the varying operation sites during refurbishment cannot yet be guaranteed. Nonetheless, current developments hold out the prospect of more efficiently usable robotic arms with an improved load to payload ratio (e.g. KUKA iiwa).

Robot programming for complex robotic deconstruction tasks

In order to prepare fundamental skills and software for the pursued robot assisted deconstruction and refurbishment process, the research started out with a couple of experiments focusing on selected aspects. Those initial research approaches are described hereinafter.

Force controlled programming for deconstruction of composite materials

As part of the research project “Robotic Façade Disassembly and Refurbishment System”, a robot assisted process for the deconstruction of external thermal insulation composite systems (ETICS)
Based on EPS insulation was developed and tested. In general, the deconstruction was focused on uncovering the raw masonry structure for the application of new, ecologically harmless and more easily recyclable insulation material.

The major challenge of the layer separation was the seamless transition of the various construction layers providing no suitable starting position for common deconstruction tools nor grippers. While the separation of those composite materials seems easily manageable for humans due to their described dexterity for even minor material differences during deconstruction, implementing the same sensitivity to robots or other machineries requires additional research and development effort.

Finally, the precise material separation (e.g. of plaster-adhesive composite and insulation) was achieved by using a common multi-tool machine with force controlled robot programming through the implementation of a KUKA iiwa and the utilization of its torque sensors. In this case, force controlled programming describes the combination of tool movements linked via movement cancellation criteria depending on forces measured by the robot (e.g. during the collision of the tool and the wall). Thereby, the individual movements can automatically be adjusted according to the spatial settings without interruption or cancellation of the total process. Furthermore, no manual robot movement or relocation has to be integrated in the deconstruction procedure and therefore uncontrolled as well as error-prone actions can be excluded.

Only a small area of the plaster-adhesive composite has to be manually removed from the insulation, afterwards the processes can be continued fully automated. The experimental procedure is depicted in Figure 7.

Figure 7. Force regulated movement of the deconstruction tool – Experiment executed in the RWTH Aachen robotic laboratory with a KUKA iiwa and a Fein Multitool (Image: Lublasser and Brell-Cokcan, Individualized Production in Architecture, RWTH Aachen University)

Intuitive human machine interaction through haptic programming

For the implementation of new technology such as robotic assistance on building sites, new ways of programming and machine integration have to be developed to achieve a high acceptance of the technology by unprepared and untrained building workers as well as an efficient human machine interaction on site.

One approach to support simple human machine interaction while alleviating fears for new technology is the “haptic programming” developed during the project “Dynamic & Interactive robotic Assistant for Novel Applications”17,18 by the chair for Individualized Production in Architecture. Haptic programming allows for direct and safe machine interaction through targeted integration of teaching options as well as soft motion modes provided by newest robot technology with torque sensors such as the KUKA iiwa. Through slight pushing of the robot by the human in predefined directions, the prepared robot program can be started, manipulated, fast-forwarded and rewound. Furthermore, the robot can be led within locally defined boundaries to capture geometric information which then allows on-site changes of the construction design to the very last minute before execution. The advantage of the haptic programming for simple human machine interaction is that no code-based programming has to be done on-site but the building worker is still able to adapt the construction work and process. For this purpose, no complex additional training in addition to a short introduction to the robot features is necessary.

This haptic programming research has already been tested with various people who are not familiar with robotics and was proofed to be successful. One application was presented at the Hannover Messe 2016 in the course of the KUKA innovation award. Here, bystanders were able to define the geometry of a rod-shaped wood structure which was then immediately produced. Furthermore, they were able to support the robot during the joining process of the rods to gain a higher accuracy of the robotic joining motion.17 The last described interaction was also tested at the Robodonien Festival 2016 in Cologne. Here, the haptic programming during the process was expanded with the options of program starting as well as fast-forwarding and rewinding to be able to operate necessary predefined movements as often as desired. In both cases, the integrated bystanders were able to interact with the robot with
only minor explanations and showed no anxious reluctance in handling the robotic process by themselves.

**GLOBAL EFFECTS OF AUTOMATION AND ROBOTIC ASSISTANCE ON CONSTRUCTION SECTOR**

As shown, the application of robotics and automation helps to directly connect different stages of the buildings life cycle. Moreover, automated machinery on site can be implemented as a data and information medium to overcome one of the biggest issues for the implementation of advanced automation on building sites - the lack of a closed *digital* process chain (Figure 8) from planning to execution on site until the final end of a buildings life cycle.10

![Figure 8. Loss of information during the building lifecycle and additional data through robot integration (Image: Lublasser and Brell-Cokcan, Individualized Production in Architecture, RWTH Aachen University)](image)

By using digitally controlled machinery for building element production, handling and manipulation, connecting various information such as material type and conditions, actual positions of new or inbuilt elements, deviations from planned execution and connecting them with the geometric information of the digital building model will be enabled. Thereby collected information can then be used as data basis for further refurbishment actions or the final building demolition. Furthermore, the data collection helps not only for one building in particular but also as statistic reference material for similar building types. Additionally, the general setup of automated machinery allows for simple integration of various sensors or camera systems. Collecting additional information with the help of those tools can help to provide a reliable data basis for building refurbishment and demolition especially of old buildings with no digital and little other information on the actual construction setup. Hereby, all building and demolition tasks become more predictable and can be planned more effectively and efficiently.

**CONCLUSION**

The paper presented a summary on the various research approaches on automated and robot assisted refurbishment and end-of-life processes in the context of the German and Japanese construction sectors. The different research aims are dedicated to different levels and scales of the general processes development. Thus, an important task for future research is to combine the results of all scales to generate a highly automated and adjustable refurbishment as well as end-of-life process and to generally push the degree of implemented automation in the construction sectors all over the world.

**References**

1. Rein, S., „Bestandsmaßnahmen stützen dauerhaft die Baunachfrage“, BBSR-Berichte KOMPAKT, Bundesinstitut für Bau, Stadt und Raumforschung (BBSR) (editor), Germany, 2009


ECO – BOX: a system of lightweight vertical urban farming and its robotic assembly & operation process

Jing Ma 1*, Kepa Iturralde 2

1 Department of Architecture, Technical University Munich, Germany
2 Chair for Building Realization and Building Robotics, Technical University Munich, Germany
* Corresponding author (mjja1020@outlook.com)

Robotic technologies are increasingly applied not only to building construction, but also to building renovation. In case of façade renovation, robotic applications can improve the safety and productivity of assembly process while diminish the disturbance to residents. Lightweight and compact elements are required especially when the buildings are old as well as the construction sites are narrow.

Design focus on the function and construction of a lightweight and customized system for urban farming, which basically works as a greenhouse attached to façade. Additionally, the system serves as a ventilator for the apartment it relates to. It is assembled and operated by robots, which can move along both horizontal and vertical rails on the façade.

Keywords: Robotics, Façade, Renovation, Lightweight System, Urban Farming, Automatic Assembly

INTRODUCTION

The idea of Eco-box (Fig. 1) is based on the renovation of façade of a residential building in Munich, which was built in 1989-1991. By extending its life cycle, robotic refurbishment provides more favorable socioeconomic and environmental capabilities than the sole construction of new buildings. 1

Because of the lack of Balcony for growing vegetables as well as adequate ventilation, the Eco-box is designed to solve both problems. This hybrid system consists of a greenhouse with solar panels on top and a mechanical ventilator at the bottom. In operation, robots move along the rails at the bottom of the system to take care of the vegetable and pick up fruits as needed.

The ecosystem is embedded with façade and the drainage system, which aims to have zero energy consumption by using solar energy and filtered water from rain. The shape of the Eco-box is designed to achieve maximum sunlight for greenhouse while not blocking the sunlight for the apartment below. A rail system attached to façade enable the automatic assembly process by robots.

DESIGN METHODS

To meet the requirements that are raised in analysis, the method Axiomatic Design is implemented in the design. Axiomatic Design was developed by Nam P.Suh, a mechanical engineering professor at MIT. Suh’s intention was to identify a set of fundamental laws or principles for engineering design and use them as the basis for a rigorous theory of design. By identifying different attributes of the design, the major principles or structures become clearer, which leads to the improvement of existing design. 2

Axiomatic Design

Axiomatic Design operates with a model of the design process that uses state spaces to describe different steps in generating design concepts.

Fig.1. The robot is picking tomatoes from Eco-box.

Fig.2. The design process from an Axiomatic Design perspective.
Consumer Attributes (CAs) – are the customer needs that the design must fulfill.

Functional Requirements (FRs) – are the variables that describe the intended behavior of the device.

Design Parameters (DPs) – are the physical characteristics of a particular design that has been specified through the design process.

Process Variables (PVs) – are the variables of the process that will result in the physical design described by the set of DPs.

The relationships among these different variables throughout the Axiomatic Design process are shown in Fig. 2.

For example, if the Consumer Attribute is to minimize the weight of the greenhouse, one of the most important Function Requirements is to find a lightweight substitute for soil. Then the Design Parameter can be: use hydroponic growing method, which uses water and nutrients instead of soil. Lastly, the Process Variable is the supply and quality of water and nutrients for growing. A detailed Axiomatic Design Table is listed as below. (Fig. 3)

---

### Eco-box

The idea of Eco-box is inspired by the wishes of people living in cities to grow their own plants in an environmental-friendly and effortless way. Instead of growing plants in traditional ways, new methods that suit the environment of cities are required. There are many advanced techniques in growing plants, one of which is hydroponic agriculture.

### Hydroponic Agriculture

A revolutionary example is the rooftop garden from restaurant Bell Book & Candle in New York³ (Fig. 4). The restaurant provides local, organic and sustainable vegetables from its own aeroponic roof-top tower garden, which uses water mist and nutrients instead of soil to achieve a lighter, faster and more environmental-friendly growing methods.

---

<table>
<thead>
<tr>
<th>Customer Domain</th>
<th>Functional Domain</th>
<th>Physical Domain</th>
<th>Process Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes (CA)</td>
<td>Requirements (FR)</td>
<td>Parameters (DP)</td>
<td>Variables (PV)</td>
</tr>
<tr>
<td>vehicle farming</td>
<td>add green houses</td>
<td>attach green houses to façade</td>
<td>green houses' weight limit due to attachment's resistance</td>
</tr>
<tr>
<td>automatic farming</td>
<td>use robot for growing, checking and picking vegetables</td>
<td>use one robot moving along rails to look after all green houses</td>
<td>different tracks and end-effectors for different tasks</td>
</tr>
<tr>
<td>energy consumption of green houses near zero</td>
<td>add solar panels</td>
<td>place transparent solar panels on the top of green houses</td>
<td>area to place sufficient solar panels</td>
</tr>
<tr>
<td>water consumption of green houses near zero</td>
<td>collect and filter rain</td>
<td>use one pipe and one filter for each row of green houses</td>
<td>size and position of pipes and filters</td>
</tr>
<tr>
<td>minimize the weight of green houses</td>
<td>find substitute for soil</td>
<td>use hydroponic growing</td>
<td>the quality of water and nutrients for growing</td>
</tr>
<tr>
<td>prevent water for growing to freeze during winter</td>
<td>heat preservation of water</td>
<td>heat up container using energy from solar panels</td>
<td></td>
</tr>
<tr>
<td>improve ventilation for interior</td>
<td>add mechanical ventilation</td>
<td>install ducts and mechanical fans</td>
<td>size of ducts and fans suitable for the existing building</td>
</tr>
<tr>
<td>fast installation</td>
<td>reduce the number of parts for installation</td>
<td>use prefabricated components</td>
<td>number of prefabricated components</td>
</tr>
<tr>
<td>do not disturb residents</td>
<td>quite and not disturbing installation</td>
<td>use small robot moving in a linear for installation</td>
<td>stability and efficiency of small robot</td>
</tr>
</tbody>
</table>

---

Another example is the 8,000 square foot greenhouse in Bronx (Fig. 5), constructed and managed by Sky Vegetables⁴, which harvests about 2,500 pounds of herbs, lettuce, kale and other green leafy produce each week. Sky Vegetable farms run on the Nutrient Film Technique (NFT), wherein all nutrients are fed into a shallow stream of water. The plants absorb what they need of the nutrients and the remainder is caught in the tank and used again. While a soil-based system can weigh up to 40 pounds per square foot — too heavy for many roofs — a hydroponic system weighs approximately 8 pounds per square foot.
Structure of Eco-box
The Eco-box works as a hybrid system with two main functions: cultivation and ventilation. Along with the two main functions are the solar energy system as well as the rain collection and filtration system, which make the Eco-box into a self-sufficient system with minimal energy input. The Eco-box consists of:
- A green house with hydroponic grow tray, which contents nutrients and water for growing plants. On one side of the grow tray is rain collector and filter that are connected to the drainage system of the building. A vegetable collecting box near the opening of the Eco-box provides convenience when the vegetables or fruits are ripe and ready to be harvested by the robot.
- A mechanical ventilator hides at the bottom of the Eco-box, which improve ventilation deep inside the apartment.
- Transparent solar panels on top of the Eco-box which provide energy for the mechanical ventilator all year round. In cold winter seasons, the heating pipes under the grow tray work to prevent the water in the hydroponic grow tray from freezing, using energy produced by solar panels. (Fig. 6, 7 & 8)

As an individual and self-sufficient system, the Eco-box can be customized by the preferences of the residents as well as the structure of the existing façade. Once the size of the Eco-box is set, users can choose what kind of vegetable or fruit they want to grow in this season, which leads to the decision of the specific kinds of nutrients and the amount of water that are needed. If the vegetable or fruit needs less sunlight as provided, shading nets can be installed inside the
greenhouse. If more light helps to the growth of the vegetable or fruit, LED-lighting on top of the greenhouse can work at nighttime to accelerate the growing process.

The irrigation system is called Nutrient Film Technique (N.F.T) system. The circulation of water and nutrients goes on with a water pump in the grow tray, which means electric maintenance is essential to avoid system failure. Other than that, the cultivation process requires little effort to go on. The harvest process of vegetable or fruit can be done by a robot with a camera and Image Processing Technology.

ROBOTIC OPERATION AND CONSTRUCTION

In recent years, a number of automatic construction methods are applied in different cases using robotic technologies. One reason is the increase of human cost in most countries. Another reason is the call for safety and efficiency in construction site. In some cases, mini-actuators (or even micro-actuators) and micro-sensors are already used for the precise positioning or user functions.

The first example is the robot developed by Taisei (Fig. 9) for the painting of exterior walls on a high-rise building with a height of 219.5m. The robot’s vertical guide rails were an integral part of the façade. In moving vertically, the robot detects the joints between concrete panels and measures its vertical distance from the joints.

Fig. 9. the robot developed by Taisei for the painting of exterior walls

The next example is the mechanized panel assembly system developed by Ballast Nedam (Fig. 10). The panels are installed using a flying scaffold suspended from a tilting arm. The tower crane uses this tilting arm to pick up the flying scaffold and take it to installation position. Using its own weight, the flying scaffold tilted into place on the proper floor. The flying scaffold then attaches the façade element to the building and then suspended itself. This is done using a hydraulic system. Once disconnected, the tilting arm can be used for the next flying scaffold.

Despite the fact that many robots have been designed considering the problems of traditional construction methods, they are not sufficient to be put into practice and truly improve the construction process. Meanwhile, it is remarked the adequacy of each body type to work in different building typologies. More lightweight and compact robots are required especially when the buildings are old as well as the construction sites are narrow. Such is the case of the installation and operation of the Eco-box.

Structure & Functions of the Robot

The robot designed for the Eco-box is a compact and multifunctional robot (Fig. 11) that moves along the horizontal rails at the bottom of the Eco-box and the vertical rails on the walls. For construction and daily operation process, only a few robots are needed according to the scale of the façade. The robot consists of one body and three robot arms with different end-effectors and functions. These robot arms can be changed according to different scenarios.

Construction and assembly process: when the robot moves along rails, two robot arms can be folded at the bottom to avoid unexpected impact. When the robot stops at a precise point and ready for the installation, two robot arms can stretch out and rotate to the proper position. Three end-effectors are taken
into consideration: one for pushing and pulling motions, one for nailing between metals and the last one for nailing between metal and concrete.

**Operation and harvest scenario:** when the construction and assembly process is finished, the two robot arms can be removed and a new robot arm with sliding control can be assembled on the outer side of the robot. A camera\(^\text{10}\) is installed at the end-effector to detect whether the fruits are ripe or not, or whether infestation of the plants occurs or not. If desired, different cutting devices can be installed at the end-effectors\(^\text{11}\) according to different kinds of fruits.

**Overall Construction Process**

The construction process is designed to be accomplished mostly on the façade by small robots, which will be practical in places that are too narrow for big robots or trucks as well as on the façade of buildings with sloping roof. The overall process is listed as follow: (Fig. 12)

1. Firstly, install vertical rails on the blank walls for the vertical movement of the robot. Then install horizontal prefabricated rails one by one in the height where Eco-boxes will locate, using only the robot.
2. As all the rails are installed, the robot carrying Eco-boxes moves along the rails and installs them in the right places.
3. All the Eco-boxes are installed. The robot can move back to the starting point and change another robot arm for different usage.
4. All the Eco-boxes are in operation. The robot is picking and delivering vegetable (tomatoes) for the residents.

**Installation of Horizontal Rails**
The horizontal rails are installed one by one using only one robot. (Fig 13) Firstly, a rail unit is installed on the facade. Then the robot hangs on the first rail unit, carrying sliders and the second rail unit. By moving sliders, the second rail unit is guided towards the place next to the first rail unit. When the second rail unit is moved to the appropriate position, it is installed and nailed both to the first unit and to the wall. Then the robot come back and carry the third unit to install, and so on.
Installation of Horizontal Rails

Installation of Eco-boxes

The installation of the Eco-boxes is accomplished by a robot and two connected horizontal rail units that move along vertical rails. Firstly, the robot assembled with protection frames is put on the two connected horizontal rail units, which forms a ‘base’ to hold one Eco-box each time. The process is listed as follow: (Fig. 14)

1. The base carries the Eco-box and the robot to move along vertical rails.
2. When reaching the turning point, the movement changes its direction from vertical to horizontal.
3. The base carries the Eco-box and the robot to move along horizontal rails.
4. The Eco-box is fixed on the pre-installed rails by the robot arms.
5. After installation of the Eco-box, the robot arms fold back to the bottom of the robot. The robot comes back along horizontal rails.
6. The robot returns to the starting point and is ready for the installation of the next Eco-box.

CONCLUSION

The current paper proposed a concept of lightweight vertical urban farming unit, which is in the form of a customized and self-sufficient greenhouse that can be integrated to the existing façade. The system called ‘Eco-box’ enables people who live in apartments without balcony to grow their own vegetables or fruits using sunlight and rain water instead of soil. Meanwhile, the integrated mechanical ventilator improves the air quality of the apartment, which is especially meaningful for old buildings. Because of the robotic assembly and operation technique, the system requires minimal manual work, which suits the needs of elderly and disabled people as well as people with busy life. Since the work is still on an initial phase, more investigations on specific techniques and materials need
to be fulfilled to further develop the concept. Some of the concepts mentioned in the paper are already well developed and successfully put into practice, such as aeroponic and hydroponic agriculture system. Some concepts like automate fruit harvesting are broadly researched but only in the beginning phase of commercialization. The integration of such concepts into the system and the coordination within the system still need to be developed.

The biggest challenge of the work is the robotic assembly and operation system. Since the majority of existing successful examples of assembly robots are big in scale and high in operation cost, a compact and lightweight robot described in the paper still requires large amount of effort to be improved and realized. Potential problems can occur in the assembly process such as too much sliding motions accelerates the aging of the facilities and adds risk to unsafety.

A research possibility is the improvement of the rails for assembly and operation. Higher stability of the structure should be taken into account, such as more frameworks and better scales of the structural elements according to their materials. Another possibility is to define the details of the robot as it is still a vague concept with proposed functions. How to fulfill all the needs that are put forward while maintain a low cost of manufactory and operation is a problem to be solved.

With more defined designs and realization of the concept, the system could be customized and applied in many building renovation cases to improve the living quality of residents as well as to introduce a more sustainable lifestyle. The concept of Eco-box is not just a product of urban farming, but also an education, in which people learn about the lifecycle of nature and a way towards better future.

References


Innovative Methods for Mold Design and Fabrication

Pierpaolo Ruttico 1*, Andrea Rossi 2, Lila Panahikazemi 3, Michele Andaloro 4

1234 Indexlab, Politecnico di Milano, Lecco, Italy
* Corresponding author (pierpaolo.ruttico@polimi.it)

This paper presents a new methodology to design and produce parametrically customizable wall components having highly expressive forms by combining algorithmic design strategies, robotic fabrication techniques and thermoforming processes. The purpose is to demonstrate the possibility of manufacturing mass-customized building components considering practical, functional and cost-effective factors. The design workflow and the manufacturing process are interwoven: geometric properties, material characteristics and fabrication techniques concur to meet the efficiency of the system. The original contribution of the research presented in this paper consists of the invention of two rapid mold manufacturing systems for mass-customized elements, which combines robotic manipulations, pick-and-place, hotwire and hot-blade cutting with thermoforming techniques. The methods presented in this paper could open up a wide range of possible developments towards mass-customization of full scale building systems and components. A number of mock-ups have been realized in order to validate the methods. The geometries that are produced are the results of designing both the form and the production process.

Keywords: Robotics, Fabrication, Mass Customization, Mold Design

INTRODUCTION

The production of individually customized molds requires the development of strategies for fast fabrication directly from algorithmically generated information. In order to achieve this, robotic technologies appear to be one of the most relevant production methods to address both ease of customization and the possibility of linking digital design information and physical construction and manufacturing principles (As explained in 1, Gramazio, F. et al 2014). Within many research institutions world-wide we find experiments on robotic foam cutting. Nevertheless, none of the experiments introduce the technique of combining foam carving and thermoforming processes for mold design and production. The original contribution of the research presented in this paper consists of the invention of the following two construction systems:
- reconfigurable mold system for mass-customized panels, which combines robotic manipulations with thermoforming techniques;
- rapid mold manufacturing system for mass-customized elements, which combines robotic hotwire and hot-blade cutting with thermoforming techniques.

The methods presented in this paper could open up a wide range of possible developments towards mass-customization of full scale building systems and components.

BACKGROUND

Variation and mass-customization in architecture

The potential of digital design and fabrication processes can best be exploited where a large number of discrete elements are combined as part of a self-similar structure. The deployment in quantity and the difference in degree between the elements allow perceiving a sense of transformation of the whole, essentially making it become greater than the sum of its parts (As explained in 2, Reiser, J., Umemoto, N. 2006). The possibility of generating formal signs of “transformation” in the design of architecture is related to a mathematical model’s ability to describe variation. In this respect, the notion of pattern has re-emerged within architectural design, specifically as a critical tool for managing large quantities of information throughout the design process. Patterns facilitate the search for order and structure within the chaotic complexities of the world surrounding us. Through variation and differentiation within the rule system of geometry and information patterns, architecture becomes increasingly meaningful and expressive (As explained in 3, Kolarevic, B., Klinger, K. 2008).

When dealing with repetition-with-variation, it is not possible to easily manage the quantity of information generated by using conventional CAD-CAM processes, therefore it is necessary to shift towards algorithmic logics. The algorithm becomes a vital tool for creation that significantly expands the design capabilities of architects and engineers. Rather than focusing on form and performance in an alternating and mutually excluding sequence, the designer has the ability – through algorithmic logics - to integrate material complexities and performance analysis in complex feedback loop, analyzing multiple layers of information within the same design environment. The designer progressively defines the search space for design explorations by specifying interrelated sets of variables and parameters and bounding them to constraints, restricting in this way the range of possible solutions to specifically selected outcomes. The
variables allow for exploration of the range of design options; whilst parameters enable the setting of variation and differentiation, constraints allow for the control of possible design options. Between Top-down strategies where the form is given a-priori – usually following aesthetic sensitivity, and Bottom-up strategies that optimize a system originating from local reciprocities to address specific performance and fabrication criteria, there is a wide spectrum of form-finding possibilities. This paper tries to address how to structure a relationship between efficiency and creativity that balances their different strengths.

Related work and shortcomings of current molding technologies
Current research in the field of digital fabrication in architecture is characterized by a shift from CNC (Computer Numerical Control) machinery towards more flexible general-purpose fabrication equipment such as industrial robots. Leading to an increasingly open design space, robotic fabrication offers the opportunity for computational design to explore a wider and more open design space. Cutting-edge research institutions and schools of architecture that embarked upon the challenge of robotic fabrication are creating new markets within the building construction industry and robots are gaining ever-more popularity (As explained in ⁷, Picon, A. 2010). In this scenario, the growing demand for complex-shaped and continuously-varying casted components for architecture has lead the development of new molding technologies capable of managing complexity with efficiency; researches in this field are following two different directions.

The first branch comprehends advanced manufacturing processes that use reconfigurable molds. These molds are generally made up of a matrix in which a series of automated/non-automated shifting components can slide, within a given dominium, in order in shape an upper elastic membrane constituting the molding surface. Nevertheless, these applications require complex machineries and the spectrum of geometries manageable by a single machine is limited so far. In particular, while these technologies may be potentially worthy for gently-curved continuous shapes, they seem to be inapplicable for geometries that feature sharp edges, small and highly complex details. Furthermore, it seems to be arduous a large-scale application of these techniques for machinery complexity and heavy-duty use maintenance reasons.

The second, where robots play a crucial role, consists of reconfigurable processes, in which continuously varied manufacturing gestures are applied to specifically programmed trajectories of robots. Most of the current mold shaping techniques employ computer numerically controlled milling and hot-wire cutting. Although milling is a highly flexible process, at an architectural scale, it becomes prohibitively time consuming (As explained in ⁷, McGee, W. 2012) and undoubtedly not cost-effective. Despite the above-mentioned shortcomings, milling technology has deep roots in the manufacturing industries and nowadays, at an industrial level, it proves itself to be the most trustworthy method in terms of quality and result continuity.

Fig.1. The molds of Palazzo Italia – Milano Expo 2015 - are generated by using a 5 axis CNC milling machine.

The milling technology has been widely explored for the production of molds to cast mass-customized panels for architectural application. Two recent high-end projects that feature mass-customized molds made by means of milling technology are Louis Vuitton Foundation in Paris and Palazzo Italia in Milan. On the other hand, hot-wire cutting holds a number of advantages when used to create formwork for casting, in fact, the removal of material in this process is essentially volumic; the cutting wire processes a surface in a single sweeping motion, whereas in milling operations the volume is removed layer-by-layer, constrained by the limited depth of the milling
bit (As explained in 7, McGee, W. 2012). Hot-wire cutting provides very fast manufacturing sessions and the quality of the overall process is continuously increasing, but a relevant geometrical constraint still persists: in fact, using a wire as a modeling tool, cutting surfaces have to be ruled ones and must extend through the whole material block, effectively constraining the possibilities of producing double curved geometries. Through pioneering projects, such as those explained in 7, McGee, W. 2012; in 8, Schwartz, T. 2011; in 9, Schwartz, T. 2012; and in 11, Brell-Cokcan, S., Braumann, J. 2014, robotic hot-tool-cutting has proved itself to be an effective shaping method; the challenge undertaken in current cutting-edge projects, such as those explained in 13, Søndergaard, A. et al 2016 and in 12, Gramazio, F., Kohler, M. 2015, is to widen the spectrum of manageable geometries and related manufacturing processes. These project are opening up to double-curved surfaces, coordinating the movements of two robots. All these developments in rapid manufacturing methodologies are also challenged by the necessity of coating the resulting surfaces for casting applications, as well as in the case of using as elements in themselves. Most of current industrial procedures rely on the application of different kind of resins to reinforce the surface of the mold and reduce imperfections. However, this appears to still be a complex, costly and time-consuming process, due to factors such as the cost of the resins themselves, the difficulty to achieve a smooth and uniform surface, as well as the high toxicity of most of these products. It appears clear how, in order to fully exploit the potential offered by the rapid manufacturing of custom molds with either reconfigurable elements or wire-cut Extruded Polystyrene (XPS) shapes, it is necessary to develop an integrated process able to connect design process, robotic manufacturing technologies and an innovative strategy for the coating of the produced surfaces.

**METHODS AND CASE STUDIES**

**Rapid mold manufacturing system for mass-customized elements**

The motion capabilities offered by robotic arms, paired with the possibility to utilize different custom end-effectors, offer endless combination of fabrication processes. In order to select the most suitable for the production of molds for continuously varied geometries, key parameters have been speed of production and reversibility/recyclability of the materials utilized. In this light, robotic hot cutting of polystyrene panels through either blades or wires appears as a key method. Different strategies have been explored for this production, combining different end effectors and robotic processes. In particular, one of the key methods developed, in opposition to most of hot modelling applications using a moveable end-effector/standing block model, adopted an approach based on the use of a vacuum-gripping end-effector that transports the block along the programmed trajectories over different modeling tools, such as hotwires and hot knives. This offers several advantages, such has the possibility of easily integrate different processes of fabrication within the same robot trajectory, by simply moving the block over different tools, and also highlight great potential for the integration of such process within larger industrial production chains, where different robots handle different steps of the manufacturing process with minimal requirements for human intervention.

Using this approach, methods have been developed for the integration of robotic hot wire and knife cutting for the production of custom mold for concrete casting. The reason for such integration lies in the ability of hot-knife carving to break a relevant geometric constraint: while a wire has two intersection points on the material block and consequently the described ruled surface has to pass through the whole thickness of the panel, with a knife it is possible to create holes, carvings and surface treatments on the panel, without the need for a cut through the entire thickness of the material. Moreover, the integration of carving with standard hotwire cutting offers the possibility to create sharp edges and kinks within the mold geometry. The method has been developed by mounting on a robotic arm a vacuum gripper handling the pre-cut material blocks, which are first carved by moving through a standing hot knife, and then subsequently cut to the correct molding height by moving through a standing hotwire cutter. The carved component is then placed back within the original boundary of the pre-cut panel, creating the hollow space where concrete can be cast.

![Fig.2. Set-up of the hot-wire (R1) (b) (c) and a hot-knife (R2) (a) manufacturing process. R1: IRB1200-7, 7Kg payload, 700mm. R2: IRB1200-5, 5Kg payload, 900mm.](image-url)
This system opens up new possibilities for architects to design more articulated and performative façades. This method proved to be able to quickly produce mass-customized molds using a 6-axis robotic arm, and also showed the possibility to operate continuously with minimal human supervision during the process. The low cost of XPS material, together with its high degree of recyclability, allows the production of customization with ease.

**Case Study: Fluid Stone**
The outlined method has been experimentally tested through the development of different paneling studies. The objectives of this research are: the development of an integrated design workflow, the experimentation of innovative manufacturing strategies, the testing of thermoforming techniques to generate coatings and the investigation on the behavior of biodynamic concrete in advanced concrete paneling. Specifically for this project, it has been casted the concrete developed by Italocementi, which so far has only been employed for the paneling system of Palazzo Italia in Milan (September 2015). This material features a very high level workability and its surface quality made it worthy the use for complex shaped architectural components. The powder mixture is composed for the 80% by recycled Carrara marble and the water-cement ratio is between 10% and 11%.

Fluid Stone project is composed by unique panels, algorithmically designed and robotically manufactured. The shape concept considers a series of cutting surfaces that model a given volume with varied inclination, depth and direction. The result is a series of carved panels, that are able to modulate the light and the energy coming from the environment. The robot programming has been done by means of Hal Robotics plug-in for Grasshopper by Thibault Schwartz, creating a link between geometrical generation and real-time robot simulation (As explained in 89, Schwartz, T. 2012). The manufacturing constraints, related to the material, the working area and the end-effectors, have been integrated in the design stage in order to make them become an integral part of the design, always available in the background for analysis and simulation (As explained in 6, Brell-Cokcan, S., Braumann, J. 2011). This way it is possible to robotically fabricate infinite design variants of the current model at every time with just a few mouse clicks and without having to go through multiple export/import steps from CAD to CAM to the robot. Collisions and insufficient tool length are detected at runtime, so that the design (i.e., the code) can be instantly revised (As explained in 6, Brell-Cokcan, S., Braumann, J. 2011). The simulation strategy has been integrated in the design process in order to develop a design that is coherent with the constructed form, influenced by the non-linearity of nature and the inherited constraints and deformation of the manufacturing process.

The proposed fabrication process for Fluid Stone project is made up of three stages: hot-modeling, thermoforming and casting.

- Hot-wire and hot-knife cutting: while most of hot modelling applications use a moveable end-effector/standing block model, it has been adopted an opposite approach consisting of a vacuum-handling end-effector that executes the programmed trajectories over the modeling tool. This way it is possible, in the same manufacturing session, to use different modelling tools at the same time, specifically hot-wire and hot-knife cutters, and to manage efficaciously blocks of different scale avoiding collisions between the end-effector and the working environment. At first a standard block of XPS have been modelled by a hot-wire that cuts out the panel outline. Subsequently, through a series of consecutive carvings - executed by a hot-blade - and cutting - executed by a hot-wire - the shape emerges from the XPS block.

![Figure3. Hot-blade carving of a XPS panel carried by an anthropomorphic robot (ABB-IRB1200-5. 5Kg payload, 900mm).](image)

From a manufacturing point of view, hot-knife carving breaks a relevant geometric constraint: while using a wire there has to be a two intersection points on the material block and the ruled surface has to pass through the panel; by utilizing a knife, it is possible to create holes and detailed surface treatments on the panel.
• Thermoforming: the XPS shapes have been draped with a PVC sheet that covers the casting side and establishes a compact and smooth surface. The mean time of the thermoforming, measured for the 65 panels, is 120 seconds per panel.

![Fig. 4. Thermoforming of the carved geometries.](image)

• Casting: the 65 manufacture molds have been casted by utilizing biodynamic concrete and after a 24 hours of maturation period the panels have been de-molded and installed on an exposition wall. Furthermore, it has been experimented the possibility to achieve two different surface finishing: GLOSSY, casting concrete directly on PVC, and MATTE, interposing a paraffin layer between XPS and PVC. Eventually, the molds can be recycled.

![Fig. 5. From top-left: Panels casting with biodynamic concrete; Resulting concrete panels; Overview of different panels geometries; Assembly of panels into final installation.](image)

The analysis undertaken on the constructed panels has shown a high-level quality of finishing with continuity on the set of 65 panels and a trustworthy adherence between the designed and the manufactured shape.

![Fig. 6. Casting and panel results over different geometries.](image)

The case study has demonstrated the applicability and the effectiveness, in terms of quality, time and costs, of the proposed strategy. The maturity of the overall technical environment may allow the application of this molding technique on large scale architectural projects.

![Fig. 7. Large-scale mold design proposal – 1face casting (top); 2faces casting (bottom).](image)

**Reconfigurable mold system for mass-customized panels**

A second production method has been developed, combining the thermoforming process with robotic pick-and-place operations, with the aim to create fully reconfigurable molds.

A robotic arm has been equipped with a permanent electromagnet, allowing it to grip and place steel cylinders of 3 different heights over the molding plate. By developing a custom algorithm for the dis-
cretization of bitmap images into 3-bands patterns, it has been possible to quickly generate different pattern options. These patterns have then fed information directly to the robot, which recomposed them by placing the cylinders in the exact location needed. Thermoforming allows then joining the different elements into one coherent elements, which can be used as a cladding itself, or again as mold for casting. After the thermoforming process, the cylinders can be easily removed and reused for the next panel, offering a process where no waste is produced for the mold production.

Fig.8. Large-scale mold 2faces casting for Palazzo Italia – Expo 2015 – by Stylcomp and Italcementi.

Fig.9. Large-scale mold 1face casting for Palazzo Italia – Expo 2015 – by Stylcomp and Italcementi.

Case Study: Free Pixel
The Free Pixels case study aimed at exploring more in detail the possibilities offered by combining robotically assembled reconfigurable molds with thermoforming processes. The aim was to exploit the potential of a system where molds can be produced with absolutely no waste material. The overall composition of the prototype is composed by the distribution of sets of cylinders of three different heights (15 - 30 - 45mm), ordered along a hexagonal grid to describe a regular circle packing. The variation of the heights of the cylinders allows describing patterns with different light and shadowing contrasts, which can be driven by either a grey-scale bitmap image, or by a scalar field.

Fig.10. Robotic pick-and-place set-up and algorithmically programmed wall.

Fig.11. Grey-scale bitmap image (left); centroids of cylinders of three different heights (right) corresponding to a grey-scale bitmap image and ordered along a hexa grid.

After several tests, the final mock-up pattern has been defined by tracing equipotential areas across a scalar field determined by a set of random charges. The selected pattern of cylinders has been then subdivided in square panels of 50cm, the maximum radius reachable by the selected fabrication robot (ABB-IRB1200-7, 7Kg payload, 700mm arm) in suspended configuration, as well as by the working volume of the thermoforming machine. For each panel, information about the exact location and height of each cylinder has been fed to the robot, computing a pick-and-place toolpath from the feeding tray (divided in three tracks, one for each height) to the placement tray. Resulting aggregations of cylinders on the tray have then been inserted in the thermoforming machine and a plastic sheet has been molded on top (Fig. 13).

In order to prevent deformations and artifacts on the surface, the pattern has been optimized by avoiding any sharp transition between different heights of the
panels. This has been also supported by simulations performed with the Kangaroo physics process, allowing for quick iterations between different pattern possibilities. Once the thermoforming process was completed, the individual cylinders have been removed from the mold and placed back in the feeding tray, reducing the total waste of the process to zero. The resulting formed panel could then be used as a cladding in itself, or become itself a mold for concrete casting.

Overall, the process offered a quick and efficient way to generate a variety of mold geometries by simply assembling basic shapes in precise patterns through the help of the robotic arm. Further explorations of the method are possible by testing the usage of different geometries for the basic elements, as well as the application of the elements on curved surfaces, creating a patterning of different single and double-curved surfaces.

**INTEGRATIVE DESIGN TOOL**

The production of cost-effective molds for customized architectural elements with continuous variation requires a shift away from the materials conventionally used in the production of molds for thermoforming applications. Materials such as extruded and expanded polystyrene allow the manufacturing of molds with speed and cost-effectiveness much higher than aluminum or polyurethane. However, these materials result in molds with a much lower resistance to stress and deformation. This is particularly relevant in the case of extruded polystyrene molds, where the low tolerance of heat of the material results in a deformation of the mold, which is accentuated on sharp edges of molded geometries. Although these deformations are in most cases small, and become relevant just in case of geometries with highly accentuated changes in orientation of the faces, it appears nevertheless necessary to develop a method for the prediction of such deformation. In particular, the aim is to develop a method directly embedded in the design process, allowing for continuous feedback between geometry and fabrication constraints.

In order to achieve this, a set of custom routines has been developed within the Grasshopper algorithmic modeling environment, taking particular advantage of the physics simulation engine Kangaroo. The method is articulated in several steps, which mirror the steps involved in the physical process of thermoforming:

- Initially, the material sheet and the mold geometry are approximated as uniform triangular meshes, with a custom resolution adapted to the level of detail of the mold. In this process, all the edges of the mold geometries are embedded in the sheet edges, in order to allow adaptation between the two geometries in the following steps. Subsequently, the sheet mesh is converted in a spring network to be deformed.
- In order to simulate the first sheet deformation due to the lifting of the mold, the vertices of the sheet mesh corresponding to the highest points of the mold are translated at the exact height of the mold vertices. This determines a first de-
formation of the material, which follows the mold without tightly adapting to it.

- Subsequently, in order to simulate the vacuum forming process, a mesh constrain behavior is applied to the sheet mesh, pulling it towards the mold geometry and achieving a first adaptation to the mold itself. Here, it appears possible to visualize adaptation problems of the sheet to the geometry, in particular in case of deep holes where the sheet would not be able to be pulled by the vacuum.

- Ultimately, in order to assess mold deformation under the heat and pressure of the sheet, a weighted Laplacian smoothing is applied to the sheet mesh, with a weight on each vertex proportional to the length of the springs connected to it. This allows assessing the areas of the sheet under higher stress, and proportionally deforming them. Variation in the weighting of the smoothing applied allows simulating the behavior under stress of different mold materials (e.g. XPS, Steel).

The analysis of the resulting deformed mesh offers relevant information for predicting the forming behavior, such as orientation angle of the surfaces, allowing for the identification of undercuts in the geometry, distance of the sheet from the mold geometry, identifying areas with difficulties in adaptation to the mold itself, and the deformation of the geometry after smoothing, identifying sharp edges which are rounded by the pressure of the heated plastic sheet.
CONCLUSION AND FUTURE DEVELOPMENTS

The proposed methods demonstrate the possibility of manufacturing mass-customized building components considering practical, functional and cost-effective factors. The results show that the proposed molding techniques can produce high-detailed and complex architectural components. Specifically, the casted shape is adherent with the designed one, the surface finishing quality is accurate and performs well for casting with both conventional concrete and advanced bio-dynamic cement. From a manufacturing standpoint the methods developed have proved themselves to be highly competitive, and both molding methods results in terms of time, cost and quality demonstrated that such strategies are able to effectively manage a mass-customized production chain.

Ultimately, the results show the maturity of the instruments and the existence of efficiencies required for the development of innovative paradigms in the construction field that allow a renewed expression of shapes, materials, performances and processes, the essence of the architectures.

Future developments of this research project include a wider design freedom, achievable through the use of custom hot-tools, such as how-aws or hot-hook. Eventually, tools made of memory-shape alloys may be designed in order to widen the spectrum of geometrical possibility. Moreover, through a dynamic real-time wire tension regulation device it could be achieved a more advanced control over the cutting process, avoiding overheating or undesired deformations.

Another branch of research will be related to thermoforming techniques. The authors are willing to include structural frames within the thermoforming process in order to optimize the structural performances of the casted elements.

Acknowledgments

The authors would like to thank the sponsors Formech, Italcementi, ABB, Carmon@Carbon, SAM carpenterie, Nieder, Polimi-Mecc. A special thank you to Luca Deblasio, Alessio Pierdomenico, Umberto Giupponi, Stefano Colleoni, Ivan Della Bella and Andrea Zani, who gave countless hours of their time towards the design work.

References

13. Søndergaard, A., Feringa, J., Brander, D., Steenstrup, K., Nørbjerg, T., Clausen, K. Odico, Aarhus School of Architecture & University of Sydney; Superform: Robotic Hot-Blade Cutting; Rob|Arch (2016)
Development of a Methodology based on Requirements Engineering for Informal Settlements upgrading in Cairo

Camilla Follini¹, Wen Pan¹, Thomas Linner¹, Wafaa Nadim², Thomas Bock¹

¹ Chair for Building Realization and Building Robotics, Technische Universität München, Germany
² The German University in Cairo, Egypt
* Corresponding author (camilla.follini@tum.de)

The phenomenon of informal settlements interests many areas of the world and is constantly expanding¹. These areas are often distinguished by the lack of regulation, cheap construction materials and poor living conditions. Nonetheless, they are as well characterized by a strong general sense of community and a quite advanced organization that the community itself generates and adapts continuously to the current need. The A²L-Mobilius project² aims to improve the quality of life of informal settlements of Egypt, by integrating technology to a system that would fit the existing situation at most. In order to achieve this intent, a methodology based on Requirements Engineering has been developed, in order to be translated in a system as end-user-oriented as possible, with the final aim of being more easily accepted. Therefore, a comprehensive study of the existing situation and stakeholder expectations has been used as the starting point. Fitting requirements, the system is meant to follow, were subsequently deducted from it. The requirements were then prioritized and the most relevant translated into functions and specifications for the project A²L-Mobilius.

Keywords: Requirements Engineering, Decentralized Processing Units, Affordable and Adaptable Building System.

INTRODUCTION: SYSTEM VISION

The A²L-Mobilius project's goal is to insert a pleasant living and working environment into the existing and individual living environment by an intelligent, modular building system, which is able to evolve and transform over time. In this project, a cell-like unit is developed, in which all the main technical units of a residential building are concentrated. The unit is meant therefore to work as a "nucleus" of the residential building. The space cell-like unit, called DPU (Decentralized Processing Unit), includes three main subsystems (one for energy production, one for mobility, one for Life-Work Balance: Mini-production unit or mini office for home). The DPU-nucleus with its subsystems will be integrated into a building kit, called A²BS (Affordable Adaptable Building System). The building kit will be designed so that it is compatible with the investigated site residential structures and in particular informal housing settlements. The building system will be able to grow or evolve over several generations within an existing informal settlement so that it gradually replaces the old unstructured environment by a more formal environment that provides better tools, technologies and living conditions for the residents. The building kit with the DPU nucleus are to be embedded in an existing site that currently no longer meets the needs of residents. This paper shows the methodology used to determine the functions and specifications of both the DPU and A²BS, and discusses the results achieved.
**BACKGROUND: CURRENT SITUATION IN EGYPT**

The Great Cairo Region (GCR) hosts a great informal area, that accommodates two thirds of the overall inhabitants of the region at the moment, and the phenomenon is expected to expand. Recent urban developments in Egypt in general did not consider the inhabitants’ needs, and consequently did not help to improve the already critical situation. The government tried to contain the spreading of informal housing by denying the provision of basic needs to informal complexes, such as water and electricity, worsening the situation and increasing the tension with local inhabitants. A solution that would address the problem to its core relies into taking into consideration the following aspects:

(1) Socio-economic issues derived from the current and expected demographic change. These issues call for a more flexible system directly involving the local inhabitants in the design process, rather than newly top-down built blocks.

(2) Increasing unemployment rate, which promotes the expansion of the informal market. If it is true that the latter provides job opportunities, its lack of regulation often translates in unsustainable working and worsening of the living condition in the settlement.

(3) Poor indoor and outdoor mobility. Similar to the job market case, the inadequacy of the public transportation system left room for the development of an informal one. Other problems concern the high traffic congestion and frequent accidents. Due to the absence of barrier-free architecture, the needs of elderly people and those with impaired mobility have been as well overlooked.

**HYPOTHESIS: ENGINEERING INFORMAL SETTLEMENTS**

Informal settlements represent one of the most spread phenomena of spontaneous architecture in the world. In order to invert the tendency of informal construction, top-down systems, even the best ones, could not stop the spreading of informal settlements, and often, brought results opposite to the ones to be achieved. This happens mainly because these systems tend to overlook the needs of the future tenants, focusing mainly on urban issues. Between the different strategies, two in particular have demonstrated flaws during the past years: urban redevelopment and legal recognition. The latter involves the amnesty of already built informal construction, usually together with a monetary exchange. However, even though this solution can control the phenomenon for a short time, it may worsen the situation, since the accepted buildings have usually several flaws, and the legality becomes dubious. Urban redevelopment consists in a firm response to informalities, usually through demolition and sanctions. Novel structures are built to replace the faulty ones, with little consideration to the existing communities. As a result, this solution has proven to be, again, temporary. On the contrary, in the past a more proactive participation of the existing community to the design process ensured solutions more reliable and able to adapt to future challenges, demonstrating how effective their feedback is in the long run. The methodology here proposed is based on requirements engineering, usually employed for product and software development. This field has been explored for the high weight it gives to the final customer input, and would therefore provide a more fitting result for the A²L-Mobilius project’s aim. The tools retrieved from requirements engineering have been thus transferred to the construction field. Given this, the goal of this research would be to provide a flexible methodology to engineer informal settlements, using the end users’ feedback as a starting point and continuous verification tool. The final aim of this method will be to achieve a holistic rational system, to be easily adjusted and mass-produced, depending on the actual environmental and societal needs.

**PROPOSED METHODOLOGY**

Given the importance of flexibility of the final system, the methodology has been divided into sub-steps, exploring different aspects of the project. The different steps developed will be explained in detail in the following sections.

**General approach**

The general structure of the project follows the broadly recognized V-Model scheme. The V-Model, initially developed for Software Engineering, structures project elements (which space from abstract phases to concrete operations) in an overall development method. Each element is strictly connected with the previous and the following one, thus representing either a result or a motive (or both) in the development process. The vertical axis of the V-Model represents a decomposition of the project, from modules up to the full system, whereas the horizontal axis represents time. The central part is the core of the system, representing the turning point of the development process, shifting from the planning stage to the practical one, and therefore is usually called the “prototype” stage. The two wings of the V-Model contain the project phases or activities and they are directly correlated. The right part is used for verification/validation of the left one, through continuous investigation after the concretization of the system. A schematic representation of the different phases of the research project, following the V-Model, has been made for better project organization, and it is shown in Fig. 2. The system has been divided in three categories (system, sub-system and module). The activities of the left part of the V are meant as preparation for the design stage. The socio-technical analysis, the stakeholder analysis, and
the requirement specification are the three main steps required in order for the design to be as accurate and tailored to final users as possible. The core part represents the design stage. The design is meant to evolve from a modular stage (units) up to the full system by integrating parts and developing a fitting overall system-architecture.

**Stakeholder analysis**

Following a first environmental analysis of the existing situation, a first stakeholder list has been compiled and periodically revised. Subsequently, stakeholders were divided into four categories: (1) Future tenants living in informal settlements, (2) Developers/contractors, who translate requirements into assets, (3) Suppliers, who provide the necessary resources to the first and second categories of stakeholders, (4) Stakeholders populating the environment (such as authorities or inhabitants of the project area). The second phase of the stakeholder analysis aimed to sort the list entries meaningfully. Therefore, firstly the role of each stakeholder in relation to the project was identified. Roles were considered either active or passive. For instance, developers will always assume an active role, whereas inhabitants of the nearby area are expected to act passively. Another important step was to give a priority index to each entry. That is, in order to identify which subjects need particular attention, and, on the other hand, who will be less affected by the project. Since a stakeholder can take position either for or against the whole project or a specific part of it, oppositions of stakeholders with high priority have to be thoughtfully considered. Given this, priority was based on a numerically countable scale, in order to have a way to compare different entries. Priority has been given considering three factors: (1) how much the stakeholder may influence the project, (2) how big is the impact of the project on the stakeholder (3) how big is the interest of the stakeholder in the project, and it is a number on a scale from one to five, with five representing the highest importance. Finally, possible correlations between stakeholders were considered. The Actors Map (Fig. 3) is a visual representation of the relationship between stakeholders. Each stakeholder is represented by a square, whose label refers to the identification number. Stakeholders are in relation with other stakeholders (square to square), groups (square to ellipse) or main categories (square to circle). Key stakeholders, derived from the prioritization phase, are highlighted in red. Generally, the dimension of the “icon” representing each stakeholder changes basing on their priority (spacing from the biggest, representing priority 5, to the smallest, priority 1). The category that has most influence on the others is the “Environment”, and therefore it has been placed in the middle of the map, having power both on tenants (in means of social obligations) and on developers, contractors and suppliers (by regulating their activities).

**Requirements analysis and prioritization**

Each project use case is an amount of functionality needed by the product to give the correct response to the stakeholders’ needs. The essence of the system is the underlying reason for having the product or accomplishing the project. As the understanding of the essence of the project evolves and matures,
the chosen stakeholders work alongside of the analysts and determine the requirements that will fit the project context. Once this stage is complete, the findings will be used to determine detailed functions and to draft the final design.

Functional requirements
Functional Requirements specify what the product must do and describe what the project has to do to support stakeholders' wishes. They are usually quantifiable and aim to a specific goal, which can be a particular behaviour or an output of the system. The domain of functional requirements is the scope of the work, the project area or domain under study. Therefore, four main categories were established, following the scope of the project:

(1) Energy: is aimed at the design of the Energy DPU-subsystem. Concerns requirements related to water, electricity, gas consumption, provision, collection, storage; power generation; pollution of air, water and environment; eventuality of roof gardening or vertical farming.

(2) Mobility: is oriented at the design of the Mobility DPU-subsystem. It has subcategories in internal and external mobility. It spaces from enhancement of the senior mobility and elimination of barrier, to street maintenance and road safety.

(3) Life-work patterns: is aimed at the Working DPU-subsystem. It concerns overall working and commuting issues.

(4) Construction: is oriented at the development of the A²BS. Its goal is the solution of the main construction issues from different points of view, such as sustainability, efficiency, safety, re-configurability, rationality. Comprehends as well the requirements related to the increase of the "formality level" of construction.

Non-functional requirements
Non Functional Requirements express the quality of the project and therefore are not always countable or easy to assess. They put constraints on functional requirements and help to concretely define and tailor them to the end-user need. NFR could be derived from the following aspects:

(1) Look and feel requirements: concern the intended final appearance. For instance, the structural element of the proposed system can be summarized as wooden frame, light steel frame, precast concrete frame or volumetric modular systems. The design needs to be durable, flexible, adaptable and affordable. The appearance of the design should not over-impact the surrounding buildings. The proposed building should respect the existing architectural characteristics of the local design.

(2) Usability and humanity requirements: what the product has to be if it was to be successfully used by its intended audience. This has to be identified through detailed design stage and by conducting use case scenario on the chosen stakeholders.

(3) Performance requirements: involve how fast, big, accurate, safe, reliable, robust, scalable, and long lasting the product should be and what capacity the product should have. For example, to install a decentralized power generation system, the design team has to take into consideration the connection of the joints of the system with the existing structure, the cost of running of such a system, and if it would be easy to train local technicians to maintain or repair it.

(4) Operational and environmental requirements: deal with the product intended operating environment. Thus it is important to assure that the local environment does neither negatively affect nor negatively be affected by the project, both interiorly and exteriorly.

(5) Maintainability and support requirements: how changeable the product must be and what kind of support is needed. This aspect needs to be considered during the design stage. There are various design method can be utilised to solve the issue, such as platform design strategy and open building design strategy.

(6) Security requirements: assure the security, confidentiality, and integrity of the product. They are usually the most controversial. For instance, it could be advantageous to install CCTV cameras and other type of surveillance technology to increase the security level of the area. However, it is not always possible, since the system cannot breach of personal privacy of the residents.

(7) Cultural requirements: represent the human and sociological factors of the people that will finally use the product. The product should integrate as much as possible in the existing settlements, in order to be easily accepted by their inhabitants.

(8) Legal requirements: concern the conformance to laws and standards. A crucial point of the project is to formalise (or at least, increase the level of formalisation of) the informal settlement construction. Therefore, the project should be conformed to the Egyptian building code.

Prioritization of requirements
There are many different ways to prioritize functional requirements. Ebert³, for instance, proposes to evaluate requirements depending on two main factors: effort and risk (regarding the development of the function). Therefore, higher priority is given to features whose development does not involve too much money or effort, and whose failure risk is consequently very low. Another famous example is the Value-Cost prioritization. This method in particular has been used throughout the project with the aim of selecting the most important features to embed in both the DPU and A²BS in the later stage. The method is based on the "Analytic Hierarchy Process"
AHP involves the building of two comparison matrices, one concerning the cost and the other the value of singular requirements. Subsequently, the eigenvalues of each matrix are computed and printed in a graph. The numbers derived, in a percent form, represent the weight of each requirement on the overall cost and value of the project. The result is a Cost-Value diagram, which renders the priority of each requirement. As mentioned, higher priority is given to requirements characterized by low-cost and high-value (Fig. 4).

Extrapolation of functions and specifications
After prioritizing requirements, the next step consisted in extrapolating one or more functions from each of those with the highest priority and discarding the others. In order to have a more reliable result, three variants of the environment were studied and simulated. Using the same method as above, three different requirement outcomes were given. Requirements with high value in all three scenarios were translated into core functions. Given that the final system is intended to be modular, core functions are considered as fixed modules to be embedded in the basic structure of the DPU. All the other requirements not discarded (i.e. relevant in at least one of the variants) have been on the contrary considered as modules to be eventually added to the core structure at need, but not essential. Basing on the requirement type, they are divided into (1) external functions, (2) partially external functions, (3) combinable functions and (4) services. The core of each subsystem has to be intended as part of the DPU nucleus. Therefore, eternal and partially external are intended respectively as part of the building and part both of the building and the nucleus. After defining functions, specifications schemes were developed. Technologies suitable for specific functions were listed with the identification letter “T” and added to each scheme. The following sections explore the outcome for each DPU-subsystem in detail.

Energy DPU-subsystem
The Energy DPU-subsystem should provide a reliable system that would respond to the needs of the community related to collection, provision, wise use and eventual production of different kind of primary resources such as electricity, gas and water. Therefore, functions have been sub-divided into five categories: (1) water, (2) recycle, (3) energy, (4) power generation, (5) pollution. Water storage, energy storage and recycling have the highest priority and were therefore treated as core elements. Other features with high priority but different application, such as provision, collection and farming are intended to be part of the building itself, rather than of the DPU, and were therefore treated as modules. In particular, provision falls under the service category.
tures, from street security to transportation. Given this, the Mobility DPU-subsystem, unlike Energy, should not be considered as a nucleus, but rather as a sum of unit parts collaborating as a whole.

![Fig. 6. Mobility sub-system: specification scheme](image)

**Home fabrication DPU-subsystem**

The Home fabrication DPU-subsystem should be considered not as a singular module, but as a part of a greater interconnected system aiming to give an alternative and more sustainable work method, and therefore to provide a higher number of workplace to decrease the unemployment rate. It must assure as well a better, healthier, safer working condition. The workspaces developed are to be embedded in larger Cloud Manufacturing systems that will allow companies to utilize a highly skilled workforce (including highly experienced elderly) by teleworking, thus avoiding traffic congestions.

![Fig. 7. Life-Work patterns sub-system: specification scheme](image)

**Conclusion and future work**

In this paper, a methodology used to achieve a holistic system to formalize informal settlements has been developed. Since the final system’s aim is to respond concretely to the existing issues both of the environment and the end users, the starting point has been set in a comprehensive environmental analysis performed by GUC, combined with a stakeholder analysis. The issues highlighted from these two sources, thoughtfully categorized and prioritized, were subsequently translated into requirements, which were then explored and sub-divided into concrete system functions. The final goal was set into create a set of three specification schemes of the three intended DPU subsystems, to be translated into a modular design system in the next phase of the project.

The system has been proven effective into the preliminary design stage, since it was able to give a rational structure to the creative process. Nevertheless, it still needs further stakeholder validation. In a future development, requirements, functions and the preliminary design will need to be verified by the end users and other parts involved, by means of questionnaires and interviews, as planned from the initial phase of the project. The feedback derived will not only prove the real effectiveness of the method, but also be a valuable base for further prioritization and research.

**References**

Restoration System For Buildings In Dense Areas

Karl Greschner\(^1\) and Kepa Iturralde\(^2\)

\(^1\)Exchange Student of Architecture, Technische Universität München, Munich, Germany
\(^2\)Department of Architecture, Technische Universität München, Munich, Germany

*karl.greschner.1@ulaval.ca, kepa.iturralde@br2.ar.tum.de

The paper discusses a possible system for the restoration and improvement of old buildings in dense areas. These buildings were often not designed to answer the criteria and needs of nowadays, but represents a vast majority of the buildings found in the cities. The work focuses on the restoration of the façade of an existing post-war building with an approach bringing forward a robotic crane, equipped with an adaptable and multitask end effector, to install a designed panel system. The article will discuss these solutions from the creation to the logistic. This student work was realized in a project course given by the Chair of Building Realization and Robotics of the Technische Universität München (TUM) in 2016.

**Keywords:** Dense Areas, Crane, End-effector, Panel System, Logistics

1. INTRODUCTION

In the new era of building sustainability and efficiency we are living in, the requirements on performance and environmental impact of new constructions keep getting higher and higher, but what happens to the buildings of the past era. These buildings that were not designed to answer today’s needs, but represent the vast majority of the existing. A good part of them can be found in central areas with difficult working environment criteria as working on different existing structures and in narrow spaces with high circulation needs during construction, which demand a fast installation. This makes the restoration of buildings in central areas one of the upcoming challenges of our time, where systems allowing a fast and flexible installation, as well as minimizing the working space needed on site, have to be developed. In that matter, robotic presents an interesting course of action through its potential for multitasking and accelerated work speed.

This paper shall present an overview of a project made for the course Special Aspect of Building Technology and Management, given by the Chair for Building Realization and Robotics of the TUM with lecturers Professor Dr.-Ing/Univ.Tokio Thomas Bock and M.Eng. Kepa Iturralde, starting by the project itself, followed by the means developed to fulfill the requirements of the project and finally, the logistic of the solution.

2. THE PROJECT

The project focuses on the façade of an existing building (Fig.1) and consists in the restoration and improvement of the existing to comply with the needs of nowadays. The goal was to have a more energy efficient building and to use robotics to develop an efficient and flexible way of doing the work that could be reused for future projects in similar context.

![Fig.1. Front Elevation of the Existing Building (west oriented)](image)

![Fig.2. Context View of the Project (the existing building is in the center of the picture)](image)
2.1 Context
The building that was chosen for the project is located in the neighborhood of Maxvorstadt (Fig.2), which is part of the central area of Munich. The building (Fig.3) itself dates back to the post-war era; it was constructed in the 1950s and has not sustained many changes since its construction. Therefore, the building was in need of maintenance and improvements, which made it a perfect fit for the task at hand.

Fig.3. Existing Building in Munich, Germany

The apartment building is constructed out of masonry and is six storeys high (attic included). The street in front of the building is a one-way street with parking places on both sides of it.

2.2 Design Approach
The design approach was based on the axiomatic design\(^1\) concept (Fig.4), which is composed of four parts. The first part consists in understanding the customers’ needs, which was for the project to evaluate the needs of the building and the future construction site. Those needs were to have a more energy efficient building and an efficient installation for the targeted market of central areas.

The second step was to define the parameters that had to be solved to satisfy these needs. For the sustainability aspect, it was to have a new finishing material for the façade to replace the old one, to have more efficient windows (the existing being old wooden windows) and to add insulation to the building that is suspected to have none. For the construction, the objective was to have a fast and flexible installation and at the same time, a secure working site.

The third aspect consisted in creating and selecting solutions for these requirements and the final one in optimizing these solutions. After a brainstorming and research, the preferred ones were the use of a panel system to have an all in one approach for the requirements of the new façade and the use of an industrial crane with a project designed end effector to facilitate the installation and to minimize the working space needed on site. These solutions will be further described in the following pages.

3. THE MEANS
The means, which are the solutions to the requirements of the project, are divided in three elements. There is the panel system, the industrial crane and the end effector, which is the most important element of the project being the bridging element between the crane and the panel system.

3.1 Panel System
The panel system was conceived to be easy to install with the use of a slot system, so that the panels can just encase in one another at the vertical junction points. This repetitive approach from the installation facilitates the use of a robotic device. The panels themselves are prefabricated off site in different sizes, according to a predetermine layout adapted to the building dimensions. The panel’s layout is composed of a grid of 5 rows per 7 columns (exclude the

<table>
<thead>
<tr>
<th>Axiomatic Design</th>
<th>Functional Domain</th>
<th>Physical Domain</th>
<th>Process Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer Domain</td>
<td>Functional requirements</td>
<td>Design parameters</td>
<td>Process variables</td>
</tr>
<tr>
<td>More energy efficient building</td>
<td>To insulate</td>
<td>Panel system with the two elements</td>
<td>Prefabricated panels off site</td>
</tr>
<tr>
<td></td>
<td>To have a new facing material for the façade</td>
<td></td>
<td>Light weight due to installation on the existing concrete structure</td>
</tr>
<tr>
<td></td>
<td>To have more efficient windows</td>
<td>New low-e windows</td>
<td>Prefabricated frame off site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fixed frame to fix on the existing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Openable windows</td>
</tr>
<tr>
<td>Efficient installation for central areas</td>
<td>To have a fast &amp; flexible installation</td>
<td>Industrial crane</td>
<td>- Weight capacity for panels and end effector</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Dimension limit due to tight working spaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Height capacity of at least 20 m</td>
</tr>
<tr>
<td></td>
<td>Multi task end effector</td>
<td>- Bidirectional rotating end effector due to flexibility requirements</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Flexible working area to enable to move panels to place them</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stabilization system to allow a precise installation of the panels</td>
<td></td>
</tr>
<tr>
<td>To have a secure working site</td>
<td>Construction fences &amp; pedestrian protection with scaffolding</td>
<td>- Height limit not to disturb the crane's work</td>
<td></td>
</tr>
</tbody>
</table>

Fig.4. Axiomatic Design Table – Final
and is made to favor panels of the same dimension to simplify the manufacturing process (Fig.5).

The panels are conceived to be efficient, durable and as light as possible to minimize the loads on the existing structure. They are composed of exterior wood cladding, extruded polystyrene insulation and a metallic support structure (Fig.7). The different layers are glued together with a highly resistant glue to minimize the thermal bridges. The choice of a wood cladding was made in a sustainable perspective to have a renewable and environmentally friendly material. As for the selection of the insulation material, it was in accordance with the efficiency requirement and the special conditions of being positioned on the exterior side of the wall.

The panels will be fixed on the existing wall with a concrete nailing gun (Fig.6). The tool is more robot oriented, being an automated tool with a simple fixation movement and with a great pin coil or magazine capacity.

The attach points are only needed on the top section of the panel, the bottom being clipped on the top section (which is already nailed) of the lower panel (Fig.6). This allows to reduce the nailing area needed on a panel without compromising the solidity of the installation. The attach points are designed to have a spacing of 3” between the fasteners and the edges of the concrete wall in order to avoid possible cracks in the concrete during the installation. The joining system of the panels is equipped with a mag-
magnetic stripe to guarantee the stability of the connection between the panels. In a robot oriented design approach, the magnetic stripe and the V-shape of the attach points facilitate the installation.

There are two types of panels: the regular panel and the window frame panel. The regular panel is the common one found on the façade wall as for the window frame panel; it is made to be inserted in the window cavities to replace the old ones. Except for the fact that they are composed of a window, their lower and upper parts are made the same as the regular panel, so that they can have the same attach and joining system as well as offering a gripping surface for the end effector.

3.2 Crane
The idea of an industrial crane came from the compact size in which they can be found and the flexibility of movement that they can procure. It makes them a perfect fit for the project environment and tasks. They can work in narrow spaces, which are found in dense areas, efficiently with their good carry capacities and sufficient working range.

After research, a Yardboss Industrial crane from Manitowoc was chosen (Fig.9). This compact telescopic crane is mainly used for plant maintenance and material handling jobs, it is simple to operate and features a carry decks and multi-mode steering allowing operations in tight corners.

Fig.8. Dimensions of the Yardboss Industrial Crane from Manitowoc

Fig.9. Yardboss Industrial Crane & Capacity Description

The compact dimensions (Fig.8) of the crane allow it to fit in the parking section of the road, so that, with a secured working zone, the circulation on the road can still proceed.

3.3 End Effector
The end effector was conceived to be a multi-task and an adaptable device in order to facilitate the different requirements of the construction process. Therefore, it is meant to be able to work with different panel dimensions in the variety of environments that can be found in central areas (Fig.10-11).
The end effector will be fixed at the end of the crane’s arm (Fig. 12). It will be equipped with a bidirectional movement system to allow flexibility for the installation of the panels. To allow the movement, the end-effector will be provided with two motors, one for the vertical rotation movement and one for the horizontal one. The bidirectional movement system will be followed by a strong support metallic structure composed of two bars welded on a plate. These two horizontal bars will be equipped with a Gear box railing system to allow the horizontal movement of the vertical bars. The vertical bars will also have a gear box railing system to allow the vertical movement of the grips and nailing gun. This double railing system will allow the end effector to adapt to the different panel sizes. On the four vertical gear boxes are fixed the vacuum grips to grab the panels and move them. On the top two gear boxes, there are two concrete nailing guns to fasten the panels to the existing wall. For the biggest panels, the four vacuum grips will be used, but for smaller panels, only the top two can be used. Finally, on the sides can be found a hydraulic stabilization system that can adapt to different surfaces and stabilize the end effector to allow a precise installation. The stabilizers also define the working space of the end effector, the panels being able to move within these extremities with the railing system.

Fig. 12. End Effector Designed for the Project
4. LOGISTIC OF THE PROJECT
The logistic of the project installation can be grouped in six main steps, which consists of secondary tasks.

Step 1 – Transport
The construction work will start by the delivery of the crane, panels and security fences by truck. Then, they will be stored on site for the duration of the work (Fig.13).

Fig.13. Step 1 of the logistic

Step 2 – Installation of the Lower Panels
The lower panels on the ground floor level will be manually installed due to the restriction of the crane’s use in lower heights spaces. First, the sidewalk on the work site will be closed and the security fences will be installed. These fences also define the moving zone of the crane to do the work. Then, the gutters and old windows on the ground floor will be removed to allow the installation of the new opening windows, that the frame will serve as a reference for the lower panel installation. Finally, the lower panels will be installed and at the end, a reference border will be fixed on top for the next step with the robotic crane (Fig.14).

Fig.14. Step 2 of the logistic

Step 4 – Installation of the New Windows
Step four consists mainly in the installation of the new prefabricated window frames panels, which will be used as a reference for the positioning of the regular panels. The windows will be installed from bottom to top and the movement of the crane will be in the secure zone (Fig.16).

Fig.16. Step 4 of the logistic

Step 5 – Installation of the Upper Panels
The installation of the upper panels uses the same principle as for the windows, they will be installed from bottom to top and the crane will work in the secure space (Fig.17).

Fig.17. Step 5 of the logistic
Step 6 – Last Steps
After the installation of the last upper panels of similar sizes, the top panels will be installed (due to their smaller size a double vacuum grip would be sufficient). Then, the top border to close the new façade will be manually installed. Finally, the work will be inspected to make sure that everything respects the standards, the protections will be removed and the crane will be retrieved by truck (Fig.18).

Fig.18. Step 6 of the logistic

5. Conclusion
In conclusion, this student project (Fig.19), dealing with a post-war building in a dense area, presents an interesting approach to the problematic. The use of a panel system to facilitate the installation combine with an industrial crane offers a flexible and adaptive way of doing things. On the other hand, this approach also puts a lot of importance on the design of the end effector, which links the two elements together. Therefore, the end effector has to be well thought and develop to ensure the success of the project.

Also, the logistic on the construction site represents an important aspect to ensure the right application of the process in reality. Therefore, the technical aspects as well as the economical and efficiency aspects should be well thought without omitting the security parameters. To push the work furthermore, it would be interesting to see if the project concept could be exported to bigger scale buildings or less dense areas.

References
Novel applications offered by Integration of Robotic Tools in BIM-based Design Workflow for Automation in Construction Processes

Silvia Meschini 1*, Kepa Iturralde 1, Thomas Linner 1, and Thomas Bock 1

1 Chair for Building Realization and Robotics, Technical University of Munich, Germany
* Corresponding author (silviamesc@gmail.com)

Nowadays the integration between existent Computer Aided Design (CAD) and Building Information Modeling (BIM) software with robotic tools such as Robot Operating System (ROS) could represent the next step towards the correct design and application of automated construction processes in the Architectural Engineering and Civil Industry (AEC). The recent wide use of BIM improved significantly the quality and productivity in AEC field since it offers an always-updated model of the building with a structured, precise and shared database made up of detailed information about every phase of its lifecycle. This facilitates the mass production of construction elements ad-hoc to be automatically installed in addition to reducing errors and omissions due to a fragmented management of information. However, BIM by itself is not sufficient to achieve neither the complete and correct representation of complex modern buildings nor the direct planning of automated construction processes both off and on-site. There is still the lack of a specific software which can be fulfilled by resorting to the knowledge of Robotics Industry. In this paper the potentialities offered by the integration of CAD,BIM and ROS were analyzed with respect to the automated production and installation of precast timber modules for the refurbishment of existing buildings and to the installation of robotic tools for the independent living of elderly. The path towards such an integration is long and hard, many aspects have to be defined, since ROS was not conceived for AEC Industry but the potentialities in terms of money and time saving, of increased quality and productivity in addition to reducing damage risks are actually big. Thus, such an integration it's worth of further attention given that it allows to exploit an open source software with many available repositories and offers the opportunity of modeling every existing robotized system beyond to enable to test in various conditions with a realistic virtual environment thanks to the possibility of importing 3D models. In this way it is possible to find out both the best configuration and the most suitable robotic system to perform each required task.

Keywords: BIM, Automation, Construction, ROS, Robotics, Building Technology

INTRODUCTION

Until now it was a quite far idea to figure out the automation of the processes that concern AEC industry due to its various and fragmented system of managing the information about the project. This was ascribable to the many figures involved lead to very different fields of technique, each one requiring a project distinct from the others and fulfilled with incompatible software. With the advent of BIM the conception of the project in its core part is dramatically changed [1]. As a matter of fact designers have an always-updated model of the building containing all the necessary data concerning each step of its lifecycle and this is allowing to obtain exact information about the actual building, systematically organized and effectively corresponding to the project in addition to sharing them between all the subjects involved in real time. Thanks to this significant improvement, waste of time and money caused by wrong design and modifications during the execution phase are significantly reduced in addition to an improved productivity. Thus we are getting close to the easy automation of the off-site and on-site construction processes [2] [3] which require the exact location and dimension of all the elements, a methodically organization of the prefabrication and construction site over to the realization of accurate measurements.

BIM provides all these information into one file so that it's easy to handle them to design the building as to be realized by automated processes. But this is not sufficient by itself since it's also essential the exact planning of the construction process with detailed information about each required task as it is highlighted in previous studies [4]. Correa [5] underlines how BIM gave a big chance to automation in construction but also how it didn't provide direct opportunities for the use of robots in construction. In fact, BIM was conceived more for planning and managing phases rather than for automated construction processes. Hence there is a lack of a specific software to directly plan the automation of construction processes and to represent the complexity of modern buildings.

This lack can be filled by taking advantage of robotics tools such as ROS [6] so that its integration with existent CAD and BIM software could be the next step for the correct design of automated construction processes and verso the concept of “Active Building” of whom necessity was pointed out by Pan et al. [7] given that modern buildings must be easy adaptable to any change that occurs during their life-cycle, not fixed entities as it was in the past. Precisely for this reason the present research aims to explore the actual potentialities offered by such an integration.

Actual software limits

Even though BIM represented a big improvement for the AEC Industry by providing us a really accurate model of the building that has made easier to han-
dle all the information about the project, the now available BIM software are not able to give all the necessary information for the automation of the off and on-site construction processes. In fact they are not software conceived to directly plan automated construction processes and test robotic systems. Moreover the present BIM-based design workflow can’t provide the dynamic design of the buildings as highlighted in previous studies [8]. It just offers a static representation of each aspect concerning the building which is a fixed “identity”, not changeable during its life-cycle (Figure 1).

At the present time there are interesting software like Autodesk Inventor and its Factory Suite that can be used to design and planning the manufacturing of the elements obtaining 3D models of the factory with all its work stations beyond to the most suitable work flow for the production. On the other hand, they cannot give a realistic simulation since they don’t allow to program the robots or CNC machines or to dynamically test robot-assisted tasks.

Hence in the panorama of the construction software is still missing one capable of easily simulating these features. Nonetheless, such software should be well useful for simulating the implementation of different kinds of sensors, robots, end-effectors, actuators in a interchangeable and flexible environment that allows to adapt the planned process to any kind of production and building.

**ROBOTIC TOOLS INTEGRATION IN BIM-BASED WORKFLOW**

The exploitation of Robotic Industry software environments such as ROS is not a news in AEC field since other researchers have took advantage of this open source software in order to theorize the modeling and simulation of complex buildings [8] or to find out the best way to auto-mate installation of precast façades elements [9]. These previous studies showed the big potentialities of using software such as ROS in reducing time and costs for the planning of automated processes enabling to identify the best workflow and the more fitting robotic tools for each task as well to hypothesize a dynamic design of the building. This is allowed by the ability to simulate every change due to occurred new needs in occupant's life without having to test nothing in reality. However these just cited studies were previous to the recent wide use of BIM-based design by technicians from all over the world and they faced some issues such as having a structured and precise data base of information about the construction progress and updating it during its developing. Nowadays, thanks to BIM-based design, it would be easier to imagine the automation of construction processes and for this purpose it could be interesting take advantage of the potentialities given by BIM and ROS integration, exploiting the possibility to import detailed and structured 3D models in a dynamic simulation environment including all the necessary and updated information about the construction elements and process.

Exploiting the big availability of open-source ROS plug-ins it would be possible to simulate the implementation of sensors, control systems, cameras, robots and to test the automation of different phases of the building life-cycle such as prefabrication tasks, planning construction processes simulated in a virtual environment, implementation of control systems to monitoring the building that allow self-diagnose and opportune interventions, simulation of refurbishment interventions when new needs occurs and the planning of the deconstruction by testing different robots and systems.

As a result of the integration between ROS, BIM and Factory Design Suite it will be possible to obtain a dynamic design of the building that allows to plan the automation of various phases of its life cycle without any expense or damage to the equipment or to the building itself. It is also possible to simulate potential interventions having an idea of the necessary tasks and tools to evaluate the actual convenience and to find out the best solution among the many offered by the automation industry in terms of time, efficiency and money expense. In this way the designed building process has a significantly improved flexibility both in the planning and in the production phases (Figure 2). It will be possible to change and to test different scenarios, process workflows, robots, machinery, end-effectors, construction layouts and immediately upgrading the BIM model with the infor-
Another advantage could be that thanks to the information offered by BIM and simulation in ROS there is the possibility of obtaining a preliminary estimation about cost and time needed for each hypothesized automated process or intervention, in addition to the extrapolation of the best sequence to achieve them.

**ROS-BIM in Mass Production of Construction Elements**

ROS and BIM can arise interest for the mass production of precast elements, since from BIM all the information about the dimension, position, materials and costs of each part are available and all the tasks which are necessary for realization are known.

![Figure 3. Schematic representation of ROS role in BIM-based design workflow for precast elements](image)

Through such tool, designers can easily know how many elements are required, their shape and dimension. These information can be used in ROS for the off-line programming of complex assembly tasks and this enables to generate instructions for the automated manufacturing and installing process (Figure 3). Moreover, designers have the possibility to simulate the assembly tasks performed by different robots and end-effectors in order to find out the best configuration and they are able to implement control systems for the correct execution of the required tasks, checking the final results.

Starting from the standardization of the manufacturing of building elements, it would be possible to reach the final task of automated installation since it will be easier when the construction elements are designed and produced expressly to be installed by robots. Such a priori work might be not strictly necessary, nonetheless it surely would make simpler the manipulation of materials by means of robots.

**ROS-BIM and the BERTIM project**

The objective of the BERTIM project [10] is to establish a new methodology for mass manufacturing process of timber modules addressed to the upgrade of existing buildings so that it can be adopted by different companies with different production lines by means of an integration of robotic, automation, traditional and new technologies. It consists of three subsystems [11], the first concerns the exact 2D-3D modules configuration with the acquisition of the building model by means of a Laser scanner. From this first step starts the design and planning in a BIM-based environment of both off and on-site processes which gives the big advantage of having an always updated model of the building including exact and actual measurements also during the execution of the works. Thus the second subsystem concerns the manufacturing process with the implementation of some automated tasks, the third subsystem concerns the installation process by means of robotic tools and both of them will be tested by simulation with saving in terms of time and cost with respect to the traditional testing systems. In order to identify a general method the simulation environment has to be flexible and interchangeable, even the robots embedded for the automation of the process must be interchangeable and quickly re-adaptable with respect to the changes of the production line.

![Figure 4. ROS and BIM integration in BERTIM project](image)

This can be allowed by ROS. In fact, exporting the model of the factory, of the construction site and of the building in ROS, a company could test the real advantages (or disadvantages) of introducing automation in its factory without damage risks and any money effort, being also able to program and plan the ideal manufacturing and installation sequences (Figure 4).

**BERTIM off-site process automation**

As assumed before, to allow the automated installation of any construction element it is required to design and fabricate it expressly with this intent. Thus, as a first step, it is important the accurate design of the connection elements and their exact placement on the modules. With regard to the connectors at the moment the first prototypes are being tested to identify the best solution, with regard to their installation the purpose is to find out an automated solution to increase companies’ productivity and contemporarily improve quality of the process by making it quicker and more accurate. Relating to this last purpose, it might be interesting the use of an arm robot to pick and place the connectors on the panels by means of the factory 3D model designed in Autodesk Inventor and taking into account the characteristics of dimen-
sion and position both of the panels and of the connectors with respect to the existing structure.

**Interchangeable scenario**

In the BERTIM project the purpose is to find out a general methodology for mass manufacturing process of timber modules which can be adopted by different companies with different plant, not just suitable for the three companies involved in the project but for any company who wants to automate its production processes. ROS would be really efficient for this purpose, since it is possible to import in its simulation environments (i.e. Rviz, Gazebo, VRep) the 3D model of the factory designed with software such as Autodesk Inventor (Figure 6) and set them as "World". This means that it might be obtained an interchangeable scenario and to test the same automated process in different companies just changing the 3D file of the "World". Hence, a company could visualize directly what would be the new asset and how to integrate some automated tasks in its production line without any effort of money but just by means of the simulation in ROS virtual "World" capable of reproducing reality.

This opportunity enables to evaluate the feasibility of the upgrading in the assembly line by means of automated processes and its actual efficiency without physic costs and saving a lot of time. It is just necessary a 3D model of the factory which could be designed with any CAD or BIM software and then imported in Rviz [12] or Gazebo [13] in collada (.dae) or STereo Lithography (.stl) format. Once they will be defined, there will also be available the BIM models of the panels and of the connectors, thus it will be possible to bring them in ROS and testing some automated tasks with the actual construction elements such as the already mentioned process of connectors’ pick and place by means of an arm robot. In a reasonably short time it would be possible to try the embedding of a robot in the production line of each of the three companies involved in the BERTIM project, looking for a system that fits for all of them but without testing in reality, thus saving time and money and preventing any damage. In future developments of this work the 3D model of each involved company will be supplied so as to obtain a simulation environment as realistic as possible. Design the 3D model of the factories involved in the project was beyond the scope of this paper which mainly deals with the evaluation of potentialities offered by the integration of robotics tools in BIM-based design environment and wanted to focus more about the actual feasibility of automated production and installation processes thanks to such an integration. However, it must be said that having a CAD file of the factory plant makes the design of the 3D model very quick and simple given that it's possible to import it in Inventor and obtain a base on which arrange various work locations.

**Evaluating the installation of an arm robot in the assembly line**

With respect to the objective of installing the connectors on the panels by means of an automated process so that the production time decreases and the quality of the products increases, it has to be considered the exploitation of a robot such as the Kinova Jaco arm (Figure 7) on the assembly line of the factories in the previous location with respect to the one where the windows are installed (Figure 8).
researcher [15] and represented a great starting point to create a customized package for the integration of Jaco arm on the assembly line of the three companies involved in BERTIM project and let the robot pick and place the connectors on the modules. Two planners are essentially required: one for the motion planning (i.e. Moveit! [16]) to reach the arm out to the position so that it can grasp the object and one for the grasp planning (i.e. Graspit! [17]) to grasp the object with the joint state determined for grasping that particular object.

At the present time all is under developing but in the future steps of this project it will be possible to substitute the table with a part of the assembly line designed in Autodesk Factory Suite and inserted in the 3D model of the factory for the realistic simulation of Jaco’s tasks. Beyond this a camera sensor will be added to the robot, get the panel’s and connector’s models from BIM and simulate the application of the connection elements on the panels to find out the best solution in terms of costs and time. As previously said, many ROS nodes are necessary to simulate the Pick and place task with Jaco: Moveit and Rviz to visualize and plan the motion, Gazebo for the simulation and implementation of the real scenario, Graspit to grasp objects. This makes all complicated, thus one of the future objective is to write a code for the automated execution of the pick and place task, avoiding the use of so many nodes contemporarily. Furthermore, now there are lot of issues to solve since sometimes Jaco lose the grasp, other times the cube slides away and sometimes there are no reasons but simply it doesn’t work or get stuck.

There are also other matters to be solved in future work, since to let Jaco be useful for the automation of the off-site production process the robot has not just to pick and place the connectors but it has to execute many others tasks. In fact, Jaco must be able to recognize the environment from whom is surrounded and the dimension of the modules to execute the correct trajectory to install the connectors. Then it has to grasp the connection elements and apply the right trajectory to place them and, finally, it has to check the final result by means of sensors that check the correct installation. With regard to the first objective of letting Jaco recognize the world which surrounds it, the better solution could be the installation of a camera which allows also the recognition of the objects in the environment. Try to find such a solution with ROS is not so complicated since there are many available plug-ins for Gazebo that allow to implement different types of sensors. Within them there is the “Camera” plug-in which provides ROS interface for simulating cameras by publishing Camera Info and Image ROS messages and it is sufficient to incorporate the description of the camera in the URDF (Unified Robot Description Format) file of the robot. Regarding the second purpose, Jaco has also to recognize the object (i.e. the connector) and the position where it has to be placed. This can be achieved with a scanner embedded on it and a smart tag or a barcode both on the panels and on the connectors. In fact, the panels are different for dimension and for the stuff installed on them, consequently the right position of the connectors will not always be the same and it has to be planned a trajectory that Jaco must
follow. However the combination of possibilities are finite and the right trajectory could be recognized from Jaco by reading the smart tag or the barcode on the modules since to each code it will correspond a trajectory for the exact displacement of the object. If there were four kind of panels of different dimensions and with different surface characteristics, there will be at least sixteen tags or codes to distinguish them (one for each panel and one for each corner of the panel). This codes will be read by the scanner on the robot which then has to find the correspondent connection element with the same tag and apply the relative planned trajectory to displace it in the correct position. The panels are not all equals but at least they are not infinite, so there is the possibility to give a finite number of trajectory to the robot, one for each panel type and then it can recognize the right trajectory by reading the codes and consequently place the connectors in the correct position.

BERTIM on-site process automation

Once the automation of the off-site construction process is planned, by means of BIM, Inventor and ROS it might obtain construction elements built ad-hoc for automated installation thus also the on-site installation process that represents the third subsystem in the BERTIM project could be automated (Figure 11). Thanks to the detailed information stored in BIM that offers us the exact dimension, geometry and position of the elements and exploiting the realistic simulation provided by ROS where the models of the building and of the panels (with the connectors embedded) can be imported, it could be possible to identify the ideal workflow for each construction task, tested to avoid any clash and to identify also the respective appropriate robot with the more suitable end-effector. Hence, this could enable to automate also the on-site installation process.

The implementation of new technologies such as sensors, assistance devices and robotic systems requires costly and long processes to test them and find out the best arrangement. In addition, it usually requires that elderly move to another accommodation and this often is the reason to give up the idea of installing assistance devices. This could be overtook using ROS since it might be imported the model of the existing house and try to integrate LISA terminals in a virtual but realistic scenario so that the elderly can visualize how their home will look after the interventions not only in an architectonic sense but also with respect to the visualization of how robots move in the house, without any physical approach and expense. Moreover many different kind of sensors, actuators and robots as assistive technologies could be tried by means of simulation in Gazebo and Rviz without any cost and risk. Exploiting ROS it could be possible to import the LISA 3D model and testing different control or assistive systems.

JACO arm in LISA bath terminal

It is a matter of fact that old people have problems even in carrying out the simplest daily activities and bathing process is one of the most problematic. In fact it requires a certain physical strength and agility to access the bath tub, two capabilities that many old people lost even if they are also required to avoid slippages or falls.

The traditional bath tub design doesn't help elderly to easy access it, thus there are many commercial solutions designed with this purpose and previous studies considered the elderly problems connected to bathing process but their solutions, even if valid, have the difficulty of requiring always an assistance (Figure 13) or an invasive upgrading work of the
existing bathroom that has to be completely refurnished [20] (Figure 14).

Thus, as final part of this preliminary study, it was tried to integrate Jaco arm in the LISA bath terminal (Figure 15) with the intent of helping elderly during the bath and doing all the connected activities safely and independently with low impact interventions. With this purpose Jaco could help elderly in getting up from the bath tub or reaching objects in high shelves or preventing falls. Another interest application could be the installation of waterproof sensors in the bath which are able to signal a long-time inactivity of people. In fact they could had a problem or fell asleep or, in the worst case, they could felt sick and be in life danger. The sensors must be able to call for help also in the case that the old person falls down and isn't able to getting up by himself.

Coming back to the first purpose of installing Jaco in the LISA bath terminal, its 3D model was converted in stl binary format by means of Autocad “Export” function and then two ways of importing it in ROS were tested: first directly in Rviz by means of the “Import file” function, in this way it might have have the stl model in the scenario and drag it in the correct position, being also able to change its scale and orientation. The second method considers of embedding the binary code in the Gazebo launch file but it is more complicated even if more precise, the first tries were intricate, thus for the moment it was exploited the first method which gives a good integration (Figure 16) even if it wasn't possible to visualize the real colors of the meshes even trying with a collada 3D file.

However, to simulate and visualize the installation of robotic tools it is more than sufficient. In future work it has to be considered another approach that is to divide the model in different meshes and then connecting them as links in the URDF file, in this way it might be more simple but also more accurate.

**HVAC systems control by means of interaction with elderly**

Another interesting application for LISA-Habitec that could be tested by means of ROS and BIM, might be the interaction between the terminals and elderly to achieve the control of internal environment conditions (i.e. air quality, temperature…) and of the elderly life itself. As a matter of fact old people have problems of dehydration or they could have memory problems that don't allow them to understand exactly when it's time to turn on or off HVAC systems or when it's time to change the air, over that it would be interesting also to monitor how long the old person didn't go outside (Since solar radiation is important to fix vitamin D for the bones) or how long he/she was seated or laying to avoid blood flow problems and so on. This could be possible taking advantage of the already implemented function of reading vital signals within LISA-walls, adding other sensors to check the activities of the person and measure air quality or control HVAC systems basing on the actual need of the person in addition to monitoring of energy consumption, being able to reach the desired condition of both thermal comfort and energy saving.

**Terminals health monitoring system**

Finally, in a project such as LISA-Habitec it could be really useful a monitoring system embedded in the terminals to check their health-state for various scopes. In fact, it is known that elderly are not so familiar with technologies nowadays, thus a sensor networks capable of signal in real time possible operation problems or the necessity of maintenance
works could be important to intervene in time, without waiting for the evident damage. This could really facilitate the independent living of old people since in this way it is possible to intervene in time, with minor costs and less impact on their life once they are used to have these assistive functions. Hence they could live in tranquility knowing that their precious assistance systems are constantly controlled and if there will occurs a problem the assistance will be instantaneously active. These kind of sensor networks can be tested in ROS before the real implementation on the terminals without any expense of time and money.

**CONCLUSION**

This paper tackled the problem of how designing and test the introduction of automated processes and domotic systems in AEC industry since there still missing a specific software that enables the direct planning of such systems. It was highlighted how BIM can give an help in this sense but also that it is not sufficient by itself, thus it was evaluated the possibility to take advantage of robotic tools typical of robotics industry and apply them within the BIM-based design workflow. In fact, there is the need of a specific software for the dynamic simulation of construction processes that allows also the planning of a detailed and precise workflow for each required task, avoiding clashes for a successful automation and the realistic representation of complex modern buildings which have many new technologies embedded that cannot be represented with classical CAD or BIM tools by themselves. This lack could be covered with the integration of a powerful instrument such as ROS in BIM-based design workflow which can give a strong push to automation in AEC industry, allowing to simulate any construction process or domotic system in a virtual ambient without risking both the construction and the robotic tools. This means having not expensive planning for automation and not losing money in tools that in the future could reveal useless or too complicated, moreover there is the possibility to visualize the process, plan it in a safety way and visualize also the final product avoiding errors or accidents both in the planning and realization phase with a consequently improvement of productivity.

In the present research it was showed many possible applications enabled by this integration between BIM and ROS which offers a lot of potentialities even if the road to reach it is not so simple. In addition to the difficulties exposed that just require time to study and try better solutions, another issue will surely be the lack of already available URDF for traditional construction machinery but it can be realized ROS packages also for them by creating a mesh file for visual representation and the URDF description to define links, joints and kinematic.

**ACKNOWLEDGEMENTS**

The BERTIM project has received funding from the European union's horizon 2020 research and innovation programme under grant agreement no 636984.

**REFERENCES**

15. https://github.com/JenniferBuehler
Affinity of a Home Robot

Hirokazu Komotori\textsuperscript{1}, Akira Mita\textsuperscript{1}

\textsuperscript{1} Department of System Design Engineering, Keio University, Kanagawa, Japan
\textsuperscript{*} Corresponding author (h.komotori@keio.jp)

In this paper a new propose for the provision of architectural space, called "Biofied building" is described, which is highly customized to the individual needs of the appropriate user. Biofied building can be seen as architecture with focus to create a convenient environment for its user, by applying biological adaption mechanisms. Therefore, a home robot is used as a sensor for the Biofied building. However, in order to live with a robot together, the user needs a certain affinity to the robot. At moment, robots are mainly used only with simple movements. In this paper the affinity change to the robot, depending on into the robot implemented contingency and variability algorithm, is investigated. For the investigation a questionnaire has been used with 20 test persons, as well as the individual personal space has been measured. According to the results, the authors suggest three movement patterns, i.e. standard, simple movement with contingency, and complicated movements with variability. The test persons experienced the three movement patterns before they measured their personal space. In conclusion, the proposed implementations of contingency and variability showed an increase in affinity of the test persons to the robot. Furthermore, an extremely strong correlation between the personal space and the questionnaire was visible.

**Keywords**: Biofied building, Kinect v2, Robot, Affinity, Contingency, Variability

**INTRODUCTION**

In the past few years, the number of single elderly person households has been increasing\textsuperscript{1}. It is considered that the increase will continue in the following years. In the single elderly person households, it is known that elderly persons are prone to illness and accidents. In fact, there are also cases such as a fatal accident by heatstroke in summer\textsuperscript{2}. However, it may also be that the emergency response is delayed in the single person households. In line with the time, the architectural space should change for each person.

For that reason, we propose the "Biofied building" for the provision of architectural space adapted to each person. Biofied building is architectural space to create a comfortable environment by applying four biological adaption\textsuperscript{3}.

- Sensory adaption: Rather than act to think of it, that of reflexive action. For example, one release the hand reflexively when touching something to hot. This biological adaption applied to the architectural space, could result in lighting that automatically turns on, when a person walks in the dark.

- Adaption by learning: The human learns from experience. For example, once after touching something hot, the human should have learned not to touch something hot again. This biological adaption applied to the architectural space, if a resident turns off the lights every time he goes to bed, automatically adjust the lighting when the resident goes to bed.

- Physiological adaption: Life has homeostasis, which is a natural inclination to try to keep a constant state. For example, the desire to return to the original state when the body temperature changes. This biological adaption applied to the architectural space by a sensor, e.g. which gets discomfort signals of the environment, get the architectural space to control, and attempt to reduce the discomfort.

**BIOFIED BUILDING**

In this section, the Biofied building is explained. Biofied building is architectural space to make a comfortable environment by applying of four biological adaption\textsuperscript{3}.

- Sensory adaption: Rather than act to think of it, that of reflexive action. For example, one release the hand reflexively when touching something to hot. This biological adaption applied to the architectural space, could result in lighting that automatically turns on, when a person walks in the dark.

- Adaption by learning: The human learns from experience. For example, once after touching something hot, the human should have learned not to touch something hot again. This biological adaption applied to the architectural space, if a resident turns off the lights every time he goes to bed, automatically adjust the lighting when the resident goes to bed.

- Physiological adaption: Life has homeostasis, which is a natural inclination to try to keep a constant state. For example, the desire to return to the original state when the body temperature changes. This biological adaption applied to the architectural space by a sensor, e.g. which gets discomfort signals of the environment, get the architectural space to control, and attempt to reduce the discomfort.
• Evolutionary adaption: Long time genetic growth process to adapt to changes in the environment. For example, humans became bipedal walking over the many million years. This biological adaption applied to the architectural space, have the residence gather information such as what could be uncomfortable to the next residents and try to counteract it.

**The Importance of the Robot**

In a “smart house” the architectural space, and sensors have been implemented, in order to provide services to the inhabitants. Smart houses provide services to get the human data by multiple embedded sensors. However, the propose focus to use a home robot as a sensor for Biofied building. There are three reasons for it.

Firstly, is because of the costs. It is necessary to get many human information for changing comfortable space for the inhabitants. If one wants to embed the sensors in the wall, it must be considered in the system from the design stage and many sensors are necessary. However, if we use a home robot as a sensor platform, costs will decrease. This is because it is possible to reduce the number of sensors to one mobile robot.

Secondly, the proposed solution can respond easily to changes in the environment. If the sensors are embedded in the walls, they can easily be hidden by furniture or pictures frames etc. While sensors that are installed in the walls cannot be moved, it is possible to move the sensors, which are mounted on a mobile robot, which is following the inhabitant.

Finally, the proposed solution can easily be maintained and updated. If an error occurs in the sensors, it will be difficult to maintain and update the sensor, if they are embedded in a wall. It is easier to change the robot with sensor for maintenance and update by sharing with a server, because they are easier to reach.

**Affinity**

Affinity means “a natural compatibility of one thing with another”. The purposed solution aims to increase the affinity by the construction of a robot and human relationship. By comparing the various movements of dog type robots, it was found that the affinity increases the more the robot moves like an animal. In addition, it was found that the affinity increases by implementing infant characteristics to a robot. However, these studies do not consider the robot-human interaction. What is required in the robot is the interaction with humans. Therefore, the authors verified, how much is the affinity increasing with the movements of the robot in relation to the behavior of a person. However, affinity cannot be expressed in numbers. Thus, the authors used personal space, in order to measure the affinity.

Personal space means “the physical space closely surrounding person, which can lead to discomfort or anxiety if encroached”. Personal space is divided into four ranges. This section explains about personal space.

- **Intimate distance**: 0~45cm
  This is the distance, where someone can be easily touched. Usually close people such as relatives and partner are allowed to enter this distance. Someone feels uncomfortable if any other person try to enter this distance.

- **Personal distance**: 45~120cm
  This is the distance to reach out a hand to each other. General distance of a conversation between friends.

- **Social distance**: 120~350cm
  This is the distance, where people cannot touch each other, but they can get in contact with the persons. This distances is normal for contact with supervisors and at formal places.

- **Public distance**: More than 350cm
  This is the distance, where one talks without particularly addressing a person. This distance is normal to a audience, e.g. such as lectures and ceremonies.

Investigations, by Kobayashi and Kurita, proved that as closer the physical distance is, as closer is the psychological distance. Moreover, this can be applied not only to human-human relationships but also to human-robot relationships. Personal space for the approach of a home robot changes by various factors.

**Evaluation of the Robot**

Affinity is necessary for home robot in space where humans and robots live together. For a person to feel affinity to the robot, there are three elements that humans evaluate in robots.
- Influence of the movement
  Since the robot is equipped with a sensor for obtaining human data, the robot should move in accordance with the residents. Speed, motion, route and smoothness are a major factor of the movement evaluation. Studies proved that that movement of robots, which is similar to humans give a good impression to the people.

- Influence of the design
  It is looks that the person evaluates first. Therefore, the impact of the design, regarding the evaluation is large. The robot without expression has a low affinity. With this robot, it is difficult to frequently change the design, i.e. size, color, shape, expression, texture, and gloss. For this reason, the influence of the design aspect is not further considered.

- Influence of the sound
  This is the easiest way when persons communicates with each other. The sound can change the impression of the partner by intonation, tone and volume. If we take communicate with robots in sound, we have to consider the disturbance due to the driving sounds of the robot. Communication in sound is influenced by external factors.

In this paper, the authors focused on the influence of movements, as well as on the impression of the robot, and on the communication through movements. Especially those changes of movements that are easily implemented, minimize the risk of external disturbance and present information in an easily perceptible way.

**EVALUATION OF THE MOTION**
This section explains the impressions the movement of the robot gives the people. There are three factors.

- Influence of contingency
  This means that an action will be repeated if it leads to good results, or it reduces the bad results. In contrast, an action is not likely to be repeated if the implications are bad, or it reduces the good ones. Actually, the authors have been experimenting with watch robots for the elderly in rest homes, and noticed that there is a tendency of the inhabitants to repeat interactions with the robot, which lead to reactions of the robot. Therefore, using contingency will increase the affinity of the home robot.

- Influence of variability
  People are interested in changes and unexpected results. It has no meaning to implement arbitrary changes regardless of the residents’ behavior, since the residents would lose interest in predicting the robot behavior, and thus in the robot all together. However, people predict the change of results at a certain probability. As a result, residents are satisfied if they expectations and the results are consistent. On the other hand people want to try again the performed interaction, if the expectations and the results were not consistent with each other.

Thus to build a relationship it is important to involve the residents emotionally. Using variability will increase the affinity of the home robot.

- Influence of the intelligence
  People are interested in robots that move intelligently. Intelligent movements makes people thinking, which leads to an increased interest. However, the authors do not propose intelligent movement, because the perception of intelligence differs largely with each individual, and it would be out of scope of the proposed solution.

**DEVICE**
The proposed solution uses “e-bio” (Figure2) as home robot in the biofied building. The authors have developed the robot with Keio University Nakazawa Laboratory. E-bio is equipped with a Kinect V2 as a sensor. A computer is mounted on the robot, which analyzes the information, obtained from the Kinect V2 and sends a command to the robot by using Bluetooth. The technical specifications of e-bio are listed in Table 1. E-bio can move faster than an adult. Hence there is no problem to use it at home.

![Fig.2. E-bio (home robot)](image)

<table>
<thead>
<tr>
<th>Table 1. Technical specifications of e-bio</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Mechanism</td>
</tr>
<tr>
<td>Size</td>
<td>460(W)×460(D)×450(H) mm</td>
</tr>
<tr>
<td>Movement mechanism</td>
<td>Two wheels</td>
</tr>
<tr>
<td>Motor</td>
<td>servomotor(15W)</td>
</tr>
<tr>
<td>Wheel diameter</td>
<td>150mm</td>
</tr>
<tr>
<td>Motor speed reduction ratio</td>
<td>4.8 : 1</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>80 : 50</td>
</tr>
<tr>
<td>Encode</td>
<td>500 pulse/ revolution</td>
</tr>
<tr>
<td>Multiplier</td>
<td>4 times</td>
</tr>
<tr>
<td>Speed (Theoretical value)</td>
<td>Maximum: 4.9m/s</td>
</tr>
</tbody>
</table>
In this section the used sensor (Kinect V2) will be described. Kinect V2 sensor (Figure 3) developed by Microsoft. Kinect V2 can obtain the systemic human data. The Kinect V2 is equipped with a RGB camera, depth camera, microphone array and an acceleration sensor. Therefore, it can obtain the several types of human data, i.e. skeleton data, depth information and color images. In addition, it is possible to differentiate between rock, paper and scissors. In this paper the skeleton recognition is mainly used.

**IMPLEMENTATION MOTION**

The authors suggest three movements called standard, simple and complication. In this experiment, there is the contingency, the robot moves in the direction of the hand person. This response pattern has been referred as a “simple” movement. In another response pattern an inconsistency has been included by having the robot not always following the movement of the hand. This pattern has been referred as “complicated”, and implements this contingency and variability. The change of the affinity due to the movement by implementation contingency and variability has been investigated.

**Standard**

This movement is only for the purpose of comparison. This movement do not implements the contingency and variability. Approach in a straight line to the subject. It was set not to feel scary by slower than walking speed of adult.

**Simple**

This movement implements the contingency setting. E-bio moved according to the human behavior. First, someone puts the e-bio in the opposite direction to the subject. The robot rotates until it is finding a measurement of human skeleton data. The experiment is started by holding scissors towards the e-bio (see Figure 4). Next, in Figure 5 is depicted that E-bio is moving in the direction of the hand. E-bio judges in the direction of hand by constantly comparing the coordinates of the right hand and the coordinates of the chest of the person. After it moved, the robot will return to its initial position, even if the arm is still held out (Figure 6). In Table 2 are the Simple movement patterns shown.

**Complication**

This movement implements the contingency and variability settings. The experiment has been performed in the same way as the Simple one (see section Implementation motion). However, there is a certain probability of having a movement opposite to the direction of the hand. It was not allowed to return to the initial position as one point in one direction (Figure 8). An example of opposite movement is given in Figure 9, in which a hand held out to the right, but the robot move to the left. Similarly, e-bio motions vary for the front and back hand movements. In Table 3 are the movements of the robot to human behavior shown.

<table>
<thead>
<tr>
<th>Direction to the hand</th>
<th>Movement of e-bio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>Rotate 30 degrees to the right</td>
</tr>
<tr>
<td></td>
<td>Return to the initial position</td>
</tr>
<tr>
<td>Left</td>
<td>Rotate 30 degrees to the left</td>
</tr>
<tr>
<td></td>
<td>Return to the initial position</td>
</tr>
<tr>
<td>Front</td>
<td>Retreats 50cm</td>
</tr>
<tr>
<td>Back</td>
<td>Forward 30cm</td>
</tr>
<tr>
<td></td>
<td>Return to the initial position</td>
</tr>
</tbody>
</table>

Table 2. Movement of e-bio (Simple)
Table 3. Movement of e-bio (Complicated)

<table>
<thead>
<tr>
<th>Direction to the hand</th>
<th>Movement of e-bio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>Rotate 30 degrees to the right</td>
</tr>
<tr>
<td>Right</td>
<td>Rotate opposite in 1/5</td>
</tr>
<tr>
<td>Left</td>
<td>Rotate 30 degrees to the left</td>
</tr>
<tr>
<td>Left</td>
<td>Rotate opposite in 1/5</td>
</tr>
<tr>
<td>Front</td>
<td>Retreat slowly</td>
</tr>
<tr>
<td>Front</td>
<td>Meandering retreat in 1/3</td>
</tr>
<tr>
<td>Back</td>
<td>Forward slowly</td>
</tr>
</tbody>
</table>

**Fig. 7. Hand position is right**

**Fig. 8. Not return to original position**

**Fig. 9. E-bio move opposite to direction the hand**

**EVALUATION METHOD**

The authors verified the affinity by the measurement of the personal space, as well as with test persons and questionnaires.

For the questionnaire, the test person had to rate his/her impressions based on the following 10 feelings, and four questions (Figure 10).

In addition, the affinity quantitatively by measurement of the personal space has been verified. It is necessary to approach the inhabitants in architectural space. It is enough to obtain the human data in personal distance from the personal space data. Therefore, it is possible for practical use, if the personal space is less than 120cm in the biofield building.

**EXPERIMENT**

The subjects were to experience the motion, answer questionnaire, and then to measure the personal space. This was performed for each of the movements.

The personal space was measured as the distance of the robot to the toe of the test person, whereas the position of the toe was declared to 0 m. The e-bio was put to a distance of 3.5 m from the test person. The test person and the robot are facing each other. The robot is approaching frontal to the test person (Figure 11.12). As soon as the test person feels uncomfortable, the test person has to ring the bell in order to indicate his/her inconvenience.

The test persons are 20 student, all with an age around 20 years.
RESULT AND CONSIDERATION

Questionnaire
After evaluating the questioners, the result is summarized and depicted in Figure 13.

As shown in Figure 13, the affinity to the robot is increasing by implementing the contingency and variability. In particular, change of cuteness is large. Affinity has increased by being relationship to the robot. The smoothness evaluation of standard was highest of the three. In other words, evaluation of the simple and complication is low. This is due to movement of simple and complication often left and right movement.
The authors used principal component analysis. The two axis, affinity and smoothness, are results of the principal component analysis of the questionnaire.

Simple results are distributed than complicated. This shows that affinity of complicated is the highest of the three.

Additional questions for the test persons:
Q1. What is your gender?
Q2. Do you have a home cleaner robot?
Q3. Do you have any pets?
A2. Yes:3 No:17
A3. Yes:4 No:16

The author investigated that there is difference in affinity by gender, having a home robot and having a pets. It investigated in two pattern of questionnaire and personal space. Additional question result was composed using the data depicted in Figure 15.

As shown in Figure 15, affinity is no difference by gender, having a home robot and having a pets, since axis is crossed in the all graphs.
Personal space
The average result of the personal space is depicted in Figure 16.

Fig. 16. Result of the personal space

Personal space became smaller in following order: Standard, simple, complicated. Many of the test persons saw the e-bio for the first time. Therefore, one of the reasons, why the personal space was shortened, is that the appropriate test person has to get used to the e-bio for the first time. The experiment showed that e-bio can be practical in Biofied building. This is because, personal space is less than 120 cm in the movement patterns of simple and complicated.

Correlation
The authors verified the correlation between the personal space and the questionnaire. The axis of personal space data was reversed. This is because the personal space is short when affinity is a high. Both affinity of complication is the highest of the three. The Figure 17 proved that the correlation of the personal space and the questionnaire is strong.

Fig. 17. Comparison the personal space and the questionnaire

Conclusion
In this study, the authors proposed movements that increase the affinity of the e-bio for residents in Biofied building.
By Implementation of the contingency from the questionnaire and personal space, the affinity of the robot was successfully increased.
Affinity was increasing by implementing not only contingency but also variability. There is an extreme-ly strong correlation between the questionnaire and personal space. In other words, the questionnaire results are good, when the personal space becomes closer. There was no difference noticed regarding gender. Also pets and home robots in the same environment showed no significant differences. This proves that the e-bio can be practical in Biofied building.

References
1. Population trends by Ministry of Internal Affairs and Communications, Ministry of Internal Affairs and Communications, the population of the elderly, http://www.stat.go.jp/data/topics/topi72
4. TOYOTA home, SMART HOUSE, http://www.toyotahome.co.jp/smarthouse/user/
5. Yoko Yamazaki “Follow up technique of small robots that inspire the affinity”, Keio University Science and Technology, Bachelor thesis 2011.
8. I, Watanabe T, Ohno Y, Koga “Elderly therapy though conversation robot having a sense of creature”
Design of Equipment and Furniture for Children based on their Height

Masayuki SATO 1

1 Department of Human Behavior and Environment Sciences, Faculty of Human Sciences, Waseda University, Japan.

This paper provides the way to consider for new environmental design through author’s research and activities. Children’s living space will be the world just different from the space we feel by the height’s of the look becoming short. When considering the design from the height, it’s necessary to ascertain what of the one in the child or other ones the standard of the height is. When you could notice some viewpoints, the new design becomes easy to be born. When considering the design for children, we have to confirm whether its angle is the angle not designer’s desire, but for children. This confirmation makes the purpose clear about “Is it the design which is why?”. It’s our theme to consider the new design confronted with each society.

Keywords: Furniture, environmental design for children, height of space

INTRODUCTION

This paper provides the way to consider for a new LISA and new furniture through author’s research and activities. My specialization is the plan of building. There are studies about various plans for architecture, but I make POE (Post-Occupancy Evaluation) important in particular, and many researchers has considered good of the efficiency at many kinds of buildings. I’ve been examining “usability and comfortability” of the environmental design judged from human viewpoints by analyzing a relation between the environment and behavior. When giving students a lecture, or the field is explained overall, we handle layout in elderly people’s facilities and layout in housing. But most of my study is advanced in a kindergarten and an elementary school. When I do design activity as a academic person, I enter between the client and the designer, adjust a design plan for both of them for their happiness.

The seen world is different from adults for children. They’re different in the size of the body needless to say. The height of its eyes depend on the size of their body. It’s important that the height of its eyes were generated by the own body. Children’s living space will be the world just different from the space we feel by the height’s of the look becoming short. We need understanding of the world children see.

After architecture and furniture for children were designed, complaints and regrets are often born. It’s important for designers to see client’s thoughts about arrangement and elevation in the room. When these thoughts and finished products aren’t identical, complaints and regrets are born. Elevation plan in the room and combines with its height deeply. Because it’s difficult for adults to consider height for children.

The design for childrens’ height has to be analyzed more and considered. This paper would like to record and suggest about the height.

Fig.1 and Fig.2 are pictures of the workshop. That held for reconstructing the kindergarten which was washed away by Tsunami (huge tidalwave made by earthquake) on the Japanese huge earthquake which has occurred in 2011. Their building was lost, but they had the budget to build in their hand by UNICEF. In this workshop, Children lie down on cardboard and trace oneself by a pen. They clipped cardboard along the pen and made each alter ego. Everyone cored an eye and made the hole where an adult looks. Adults can understand the viewpoint of the child by the height of the same eye. The adults who participated say "I knew, but I could notice that it's low once more." through the experience spent by the height of the child's eye. AYAKO gathered this way1. We made that developed for the process of architectural design.

These Alter ego was reduced and put in the construction model immediately at this workshop. Staffs for kindergarten and Children could imagine new construction.

Thus child's growth and the design which aimed at the height of the eye are important.

Fig.1. Left: Sleeping on the cardboard and tracing the body., Right: Children’s alter ego made with cardboard
THE HEIGHT OF THE THING IS CHANGED EVERY AGE.
When I say easily, The height of the furniture is becoming high. As the size of the clothes becomes big. Fig.2 and Fig.3 are pictures of the Kinderkrippe (Day care center). The height of the window is changed according to the age.

Even if these architectural environments suit the age, these may not be arranged everywhere. These should be made according to the children's activities. Fig.4 is the example behavior of one child was recorded. A cross direction in the figure is a time axis. I classified child's behavior every “posture” as “standing”, “sitting”, “lying” and “making dizzy”. The person painted blackly means moving, the person painted whitely means stopping. This was recorded like musical sheet. Every second was recorded using a video. More than 40 people were checked, so much was understood. Since concerned to the height in particular, they always sit down or sprawl on the floor in front of their own shelf in their classrooms immediately after Children went to kindergarten. There are a lot of white people from 9:21 to 9:25 in Fig.4, but that's the record on which he sat down. From these results, I found that the place where they sit down and the place where the turn can be looked around calmly is effective at the time when they have come to the kindergarten.

It's a window of Fig.5 that this result was received and proposed. An infant often looked around while sitting on the floor close to own shelf, so the window was opened here. It’s possible to see their friends going like Fig.5. Fig.6 is the outward appearance of Fig.5., and means "The form is based on a human behavior” in Fig.6.

I designed Fig. 2 and Fig. 3 by applying Fig.4, 5 and 6.
CHILDREN’S FURNITURE CHANGES ACCORDING TO THE HEIGHT OF ADULTS

The height changes relatively as the feature of this way.

There are usually infants with adults, so design standards for children is adjusted to Adult’s standard. For example when making the height of the table for adults, the height of the child’s chair is high. When only child’s growth is considered, it’s a general way of thinking that the distance from a floor to the seat surface becomes big. But the bigger a Child grows, the lower we have to give the height of the seat surface from a floor is becoming in this case. For example something near this way of thinking is “Tripp Trapp” by STOKKE\textsuperscript{2} known widely.

Fig. 7 is the day care center where a pharmacy was converted. Adults can see outside, but Children can’t see outside from a cause of the height of this window. So I proposed that children are able to look at outside by making the floor high. Conversion is proper at Europe, but it has just become a little much in Japan that a converted building is used. Understanding is still shallow for a way of thinking in Japan. This Conversion is also designed in damage area of huge earthquake in 2011. Tsunami had come to the neighborhood right now, but a building in the area where I have received no water was used. This was built in the area where there are a lot of people who lost assets because of the earthquake. There is meaning that the lady who would like to work is supported. When we use the size of Adult’s standard for the design of children like this case, scrupulous attention is needed. It's because it's easy to become negligent of the angle for children. For example a child can't insist and explain about crampedness. While we don't notice, a stress is being given to children.

When seeing the design of the place where there are children with adults, I ask in what there is a standard of the height. A staff often says “Because the place where an adult works.” as the reason. For a reason “to fit the everyday environment”, it can be understood. But it’s difficult that behavior settings with a lot of adult convenience become the location for a child. When I aimed at only an adult and a child. There are 2 roughly divided above. A) when only child's growth was seen. B) when the design size of the child is changed according to the adult.

CHILDREN’S FURNITURE CHANGES ACCORDING TO THE [SOMETHING].

[Something] changes according to the purpose of design.

When I look back to A) and B). When you could notice some viewpoints, the new design becomes easy to be born. When considering the design for children, we have to confirm whether its angle is the angle not designer's desire, but for children. This confirmation makes the purpose clear about "Is it the design which is why?".

Fig. 8 is a playground equipment to catch a cicada. I opened up a workshop with staffs for considering about “wanting children to experience in the kindergarten”. The workshop decided the theme called "catching a cicada". After having designed it in laboratory members, We produced the equipment with infants’ fathers. We prepared for a log different in height to be able to enjoy simple molding while fathers made it.

I had considered this design through imaging height of a cicada which stops at a tree.
Fig. 9. is a classroom in an elementary school. Azusasekkei which participates in a common design of 2020 stadiums of Tokyo Olympic Games was designing. After that middle corridor is arranged during two classes decided, I was consulted. There were almost no walls to the middle corridor in a classroom, so there was an opposite opinion from School Board and a legislature. I entered between the local government and the design office, and I suggested about the pattern of the wall and its meaning were indicated.

There was a law the ceiling height of the school classroom has to set to 3.0m in Japan, but the Ministry of Education did the inspection which abolishes the number which had no data. I took part in this project held by National Institute for Educational Policy Research. We set a construction room of the height of the 2.7m and the 2.4m as well as a classroom with the height of the usual 3.0m and so lectured. We prepared a construction room of the height of the 2.7m and the 2.4m by lowering the ceiling as well as a classroom with the height of the usual 3.0m. Children had time like usual for two weeks. We did a questionnaire and a behavior observation survey on the first and last day.

We found out that children’s concentration is chipped off when a teacher’s hand approaches the ceiling and children look forward something to see. The value of the room of 3.0m wasn't best, and the 2.7m room got best evaluation in three rooms. I expected that 3.0m was best before a study. This study made it so clear that high evaluation may not be obtained that it was high-ceilinged

This study was the study to consider the height of the ceiling. But when I paraphrased the above, Concentration of a lecture is made by Environments that distract when a child sees and a teacher move easily in. I received the result and proposed two (Fig10).

1) The large opening which was behind the teacher’s platform is canceled. 2) A corner in a platform makes a wall and makes outside the classroom difficult to be seen to a middle corridor.

Reverse wall between two classrooms was needed from a reason on the construction structure, classrooms with several patterns were made in accordance with total three principles.

Evaluation is bad for a school which has a middle corridor. Because a middle corridor will be often dark and whole school will be a dark image. But there was a concept that middle corridor is light and is related to activity in the classroom at this school, so the wall which closed perfectly wasn't made. There is also layout which can go out to a middle corridor immediately from a desk by the pattern of the wall. Sound environment was opened, but a best was done by using acoustic material for the whole wall.

It's important to make sure that the child can look around as it has been told to here. But the environment that children can't look around in becomes important for a child to make concentration. Whether it opens or closes is changing with the purpose.

Fig. 10. About how to close and open a classroom to middle corridor. Fig 9 is the photo judged from a right picture of Fig.10.
Fig.11 is also the project that we rebuilt nursery center that washed away by Tsunami in 2011. This facility moved to the hill where Tsunami doesn’t come. We had decided while consulting with staff about layout of rooms. But we had to build in the limited area very small at a site on the rock, I proposed using architectural devices, such as a wall in the nursery room will remove and a wall will change a stage by falling down. Fig.12 is five-year old’s of room and two-years old’s of wall. This is the picture seen from five-years old room. The lower part is the space where desks and chairs are stored, when taking out them, children can enter here. The upper part is a closet from two-years old room side. Something staffs don’t want infants to touch is stored. Such space is often made with the height of the 90cm, and is set between the one building in recent years from population decrease, decrease in the number of children and increase of the senior citizen percentage. The facilities one building in recent years from population decrease, decrease in the number of children and increase of the senior citizen percentage. The facilities are increasing by changing those scale of facilities small. The former design until now treated the theme between one person and one physical environment. But like the above, facilities try to be one to correspond to various tenderhearted needs. In other words, that’s the direction where a way of thinking with the large-scale design for resolving a social problem are desired beyond human engineering, the care and so on. Area needs will be looked for from now on, and the sharing is developed. There is a possibility that the design born by that will be not general and be the individual design. But it’ll be the design which settles individual social problem. It’s my theme to consider the new design confronted with each society.

References
1. Edited by Architectural Institute of Japan, “Residence / town / the earth” The workshop where a relation with itself is found Rakuraku Kenchiku Rakuraku Toshi” (楽々建築・楽々都市) , Gihoudou, March, 2011.

FUTURE PROSPECTS: DESIGN OF HEIGHT FOR CHILDREN AS WELL AS SOCIETY AND ARCHITECTURE DIVERSITY
A lot of new kinds of buildings have been born according to the request of the respective fields after World War II in Japan. Public facilities are built as one building in recent years from population decrease, decrease in the number of children and increase of the senior citizen percentage. The facilities where not something with the close kind of elementary schools and junior high schools, but facilities for elderly people and children are made together are increasing. The facilities connected by one door, something to associate has increased.

In other words, the design for the various people who coexist is needed. The designers are going to make the design concept that it’s applied to the various situations.

In addition to that, Because there are many waiting children and elderly people without moving into, the case a facility built in a park and set in a vacant room are increasing by changing those scale of facilities small.

The former design until now treated the theme between one person and one physical environment. But like the above, facilities try to be one to correspond to various tenderhearted needs. In other words, that’s the direction where a way of thinking with the large-scale design for resolving a social problem are desired beyond human engineering, the care and so on. Area needs will be looked for from now on, and the sharing is developed. There is a possibility that the design born by that will be not general and be the individual design. But it’ll be the design which settles individual social problem. It’s my theme to consider the new design confronted with each society.