SMARTBEE: A Framework of Single/Multi-task On-site Adaptable Renovation Robot Technology for Building Engineering Enhancement

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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*

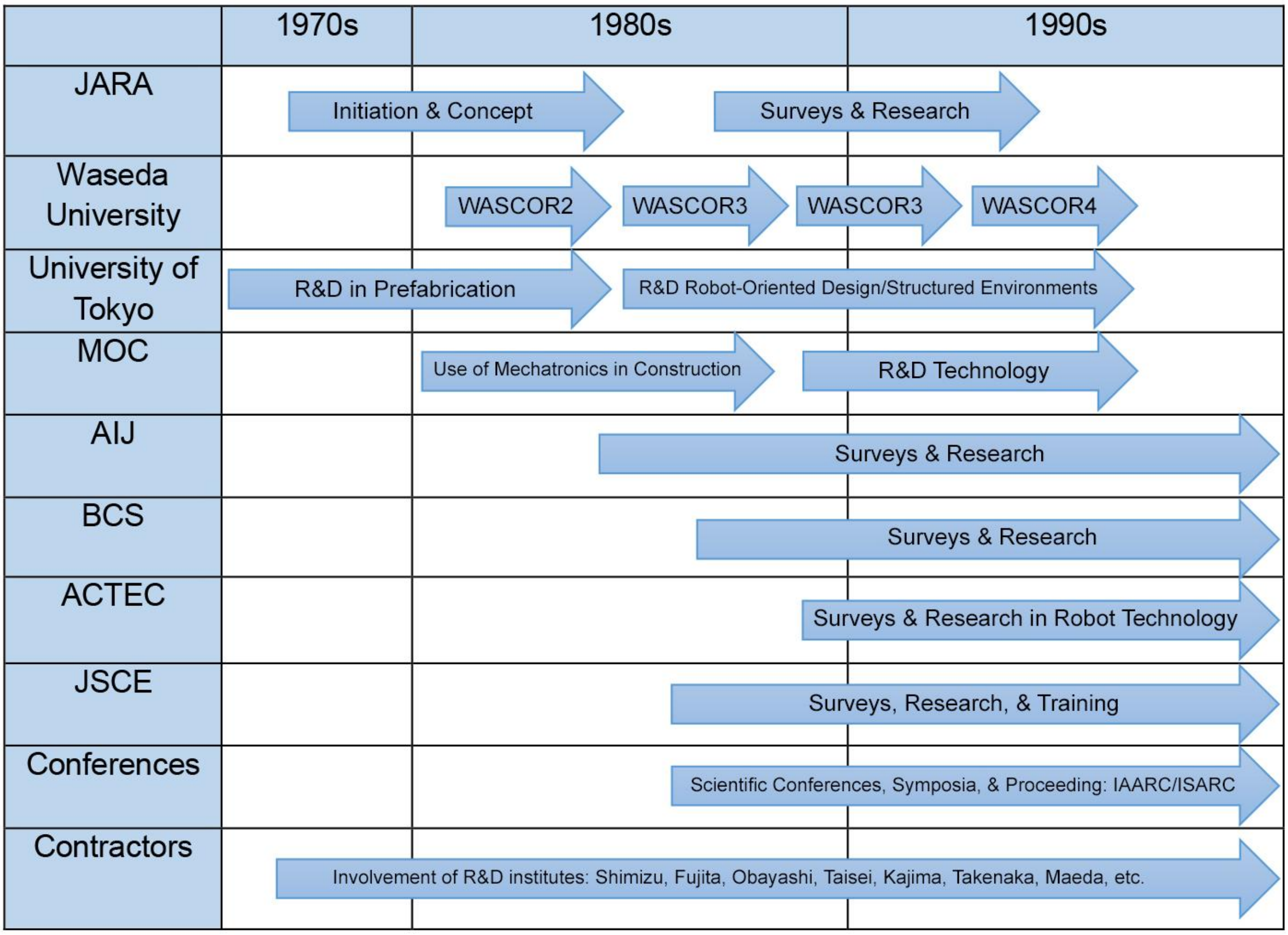
INTRODUCTION

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 technology[1]. 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 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[1] and Hasegawa, 1999[2])



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.

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

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 maximized. 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[3], Automatic Modular Assembly System (AMAS)[4], Collective Construction with Robot Swarms[5], 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[5]. 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,

(16) 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[6]. 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).

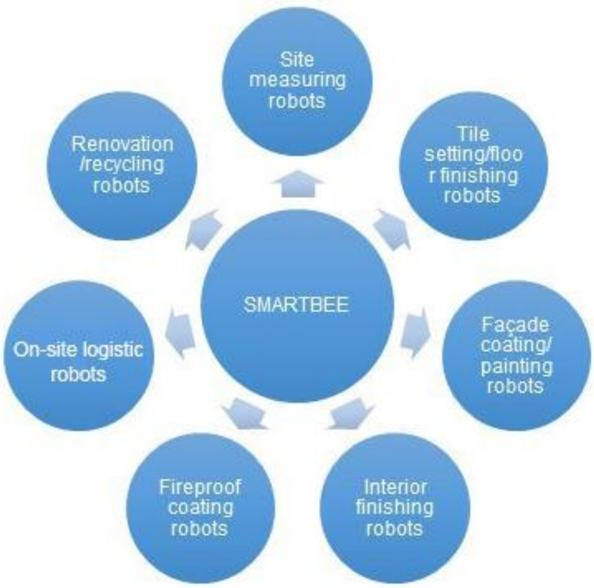


Fig.2. Integration of SMARTBEE platform

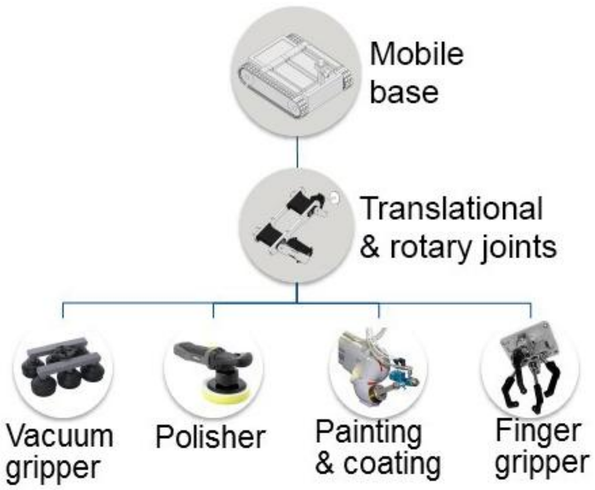


Fig.3. Modularized SMARTBEE robot system with various end-effectors

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[7].

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[8], 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.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)

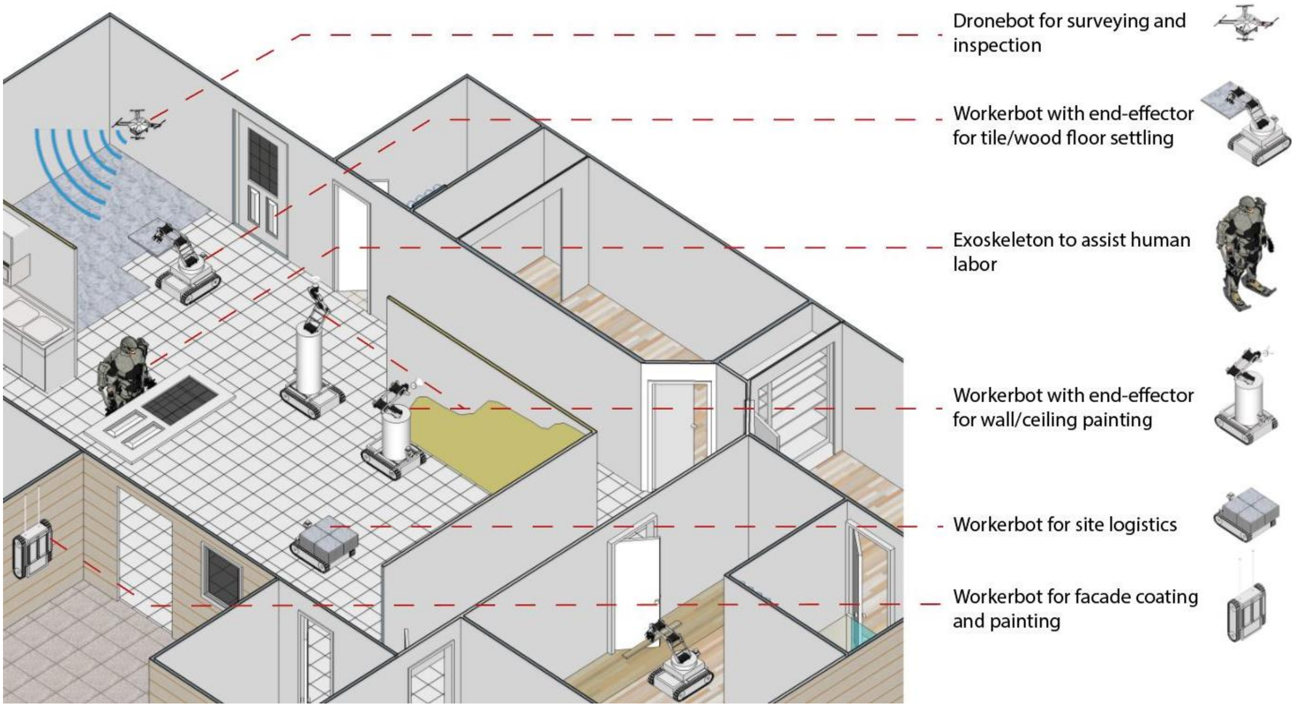


Fig.5. In a typical renovation job site, various STCRs of SMARTBEE will coordinate with each other to work properly and simultaneously

IMPLEMENTATION

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) [9], 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 ZERO-PLUS[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, STCRs 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 of 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 these 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.

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