Concept of a Robot Assisted On-Site Deconstruction Approach for Reusing Concrete Walls

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Abstract -

Construction and Demolition Waste (CDW) is one of the major waste streams in the EU by mass, accounting for 374 million tons in 2016 (excluding excavated soil), and is made up of a variety of components. Many of them can include dangerous materials and pose specific concerns to the environment and human occupants if not separated at source, but they also have a high resource value and great potential for recycling and reuse if extracted through a more controlled deconstruction process. Current deconstruction methods are ineffective in terms of being minimally invasive (air and noise pollution, destruction from tremors of explosions or abrupt demolition using explosives), safe or efficient. Furthermore, conventional methodologies fail to integrate modern technology (robots, remote sensing, and so on) in a systematic manner. This research work explores the shortcomings and strengths of previous approaches and provides conceptual approaches for robot-assisted deconstruction using the example of concrete walls.

Keywords -

robot-assisted deconstruction, construction robots, reusing construction material, automated deconstruction

1 Introduction

Construction and demolition waste (CDW) is one of the most voluminous waste streams generated in the EU. About 30% of all waste comes from construction and demolition (CD) [1]. By 2030, over two-thirds of all in-use material stock in the building sector will be 50 years old [2]. In the following decade, they will reach the end of their lives. The end-of-life product chain must be improved to guarantee that these materials may be used as secondary resources in another cycle. However, the performance of the proposed approach is limited in terms of working cubic meters per hour compared to the conventional methods.

Currently, despite the enormous share of CDW in the global waste stream, in some countries, the disposal rates of the mineral wastes amount up to over 90%, indicating a significant upside potential for recycling and reuse of these high-valued materials. Moreover, as depicted in Fig. 1, most of the CDW consists of valuable metal and mineral waste (concrete and ceramics). So far, the demand for high manual labor has restricted the recycling and reusing option.

Building deconstruction and demolition are two separate processes: While demolition is the science and engineering of breaking down structures safely and quickly, deconstruction is the process of dismantling a structure while keeping elements and materials for reuse. The building elements are shredded into little bits by large demolition equipment in the conventional demolition process. The deconstruction process for material reuse is more careful and time-consuming: The removal of hazardous materials has to be ensured comprehensively for their later utilization. Furthermore, to optimize the possibility for reuse, the concrete blocks cannot be shredded in a rough and quick manner but must be cut precisely and without damage.

Teleoperated hydraulic devices with various attachments are often utilized on building sites. They have a large number of applications, are mobile, and have a quick turnaround time. Material modification, however, is not feasible owing to the lack of local precision. Furthermore, substances hazardous, such as asbestos, are released during demolition, implying a significant health danger to employees. Consequently, only a few current deconstruction techniques address the reuse option, even though several research studies have previously found the potential for reuse of building components.

In line with these problems, this work investigates the possible advance in the current material chain by increasing the reusing rate of construction components via semi-automated processes with deconstruction robots. Advanced and proven robotic technology will be used to enable the accurate and automated cutting process of components. For this purpose, existing demolition machines will be adapted contrary to common methods where completely new robot systems are developed from scratch. In this way, proven robotic technology will be integrated more easily into reliable construction machines so that deconstruction tasks can be semi-automated with fewer efforts and risks.

2 State of the art

2.1 Demands for robotically controlled deconstruction

The changes in social and environmental requirements necessitate efficient appraisal of existing buildings' potential for refurbishment, environmental risk, and recycling. While current research into sustainable construction considers deconstruction a critical design factor, the most significant part of existing buildings was not optimized for this life-cycle stage. Demolition waste accounts for almost 30% of all waste produced in the EU and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos, and excavated soil, many of which can be recycled. Despite the intrinsic material value, the potential for material harvest is not fully exploited (recycling and recovery vary between 10% and 90% across the EU [3]). Moreover, deconstruction of old building materials often comes with significant health risks for construction workers. Current strategies are struggling to handle dust and hazardous materials in an affordable manner that sufficiently protects the workers involved. This adds to the rising issue of the construction industry as an unattractive employer with low worker retention.

Especially in marginal, low participation areas, the housing sector's degrowth of 3.8% is expected until 2030. Up to 2030, there will be a vacancy rate of 1.5 million buildings. In recent years 370.000 buildings in the east of Germany were demolished, as they were not used. Since 2001 the German government is actively supporting the program called "Program Städtebau" to demolish these buildings. However, as the areas suffer from the low participation rate, the question of how to execute the planned construction efforts remains unanswered.

On the other hand, the big European cities suffer from the degradation of construction efforts. As European Union statistics show six million people, or 5% of EU population, suffer from severe housing deprivation [4]. The issue of repurposing is also becoming increasingly important, as new regulations for environmental pollution (noise, dust, waste, and so on) in these big cities are being introduced.

2.2 Concrete Walls

Every year, approximately 55.5 million tonnes of valuable mineral wastes (i.e., bricks,sand-lime bricks, porous and concrete) are generated from construction industry. Here, concrete plays a vital role, as around 42% of used materials in the construction industry is made of concrete. At the same time, approximately 12 million tonnes of concrete waste are generated every year. Although most of the concrete wastes are recycled in the highway construction and paving, a significant amount of resources are consumed for the down- and upcycling.

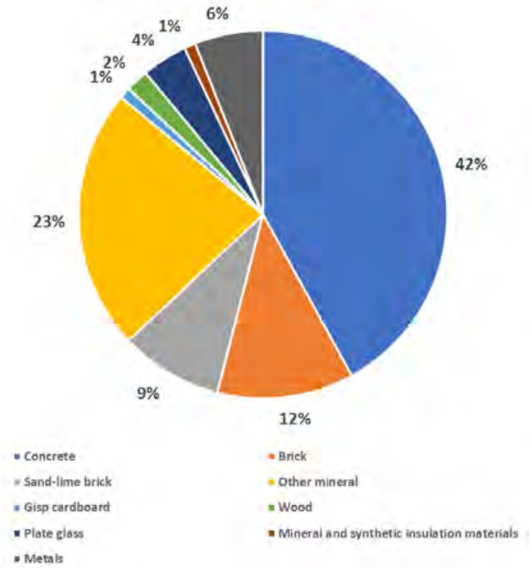


Figure 1. Used material resources in the construction industry [5]

2.3 Deconstruction of Concrete Walls

The following section describes the different methods currently used in deconstruction and renovation. Only those technologies are considered that are suitable for non-destructive dismantling or reuse. Here, experimental methods, which are still under development but have importance for future processes, are distinguished from conventional methods commonly employed on the market.

2.3.1 Conventional Deconstruction Methods of Concrete Walls

In Fig. 2, the conventional deconstruction machines for cutting construction materials are listed, which are already finding broad applications.

The summary in Fig. 2 clearly shows the limitation of the existing deconstruction methods: despite the continuous developments in hardware components, the level of autonomy has been stagnant, as most of the operations still have to be manually done.

2.3.2 Automated Deconstruction of Concrete Walls

First attempts in the 1970's from Japan, ranging from asbestos removal processes from surfaces to a cutting ma-

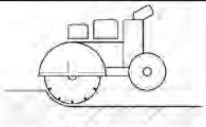
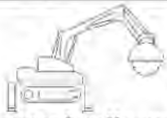
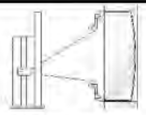
	Functionality	Materials	Degree of automation
 Wall saw	The system consists of three main elements: i) the concrete saw blade (saw blade diameter between 60 and 160 cm), ii) a drive for the saw blade (hydraulic or electric), and iii) a rail along which the driver travels. The rail can be mounted on the wall horizontally and vertically. The saw slides along the rail with the help of an integrated motor, ensuring a clean and precise cut.	The saw can be used for concrete, brick, foam concrete.	Some saws, for instance, from the company Hilti have integrated an assistance programs that can automate the cutting process. The saw assembly is still done manually, which is very time-consuming and cost-intensive.
 Floor saw	The floor saw is cutting equipment that rolls over the floor on rollers. Unlike the wall saw, the sawing device is mounted on a trolley. A saw is guided along a surface by rollers, similar to a wall saw, and can be lowered into the material to process the cutting step by step.	The saw can be used for concrete and asphalt.	Some machines can adjust their speed automatically, as they have electric guidance.
 Mounted wall saw	This particular type of wall saw is developed for use with a hydraulic manipulator. Unlike the wall saw, the saw is attached to the retaining plate of the manipulator. The operator guides the saw by remotely teleoperating the manipulator.	Materials such as concrete, stone, and metals can be cut.	The machine is manually teleoperated.
 Wire saw	A diamond saw wire is driven by a motor and tensioned with high pressure on the surface to be sliced. Pulleys guide the diamond wire in a closed circuit where the wire tension is kept constant.	This machine can be used to cut large components from reinforced concrete.	Guiding the wire saw requires a high degree of manual control. Currently, only the tension of the saw is adjusted automatically.

Figure 2. Summary of conventionally available deconstruction machinery

chine using a water jet, demonstrate that there is a great economic and ecological potential for robotic use in deconstruction to raise the recycling rates and employ new concepts of building component reuse and material harvest instead of total demolition and disposal as waste [6]. However, introducing the first robotics system on the deconstruction site resulted in several issues, some coming from the primitive human-machine-interface (HMI) and highly specified custom designs of the developed systems. To address this issue, researchers investigated the potential of the industrial robot-aided deconstruction approach [7, 8] and also the impact of a new HMI method, for instance based on a laser designation.

However, industrial robots typically suffer from a low payload/weight ratio. Also, they are mostly designed for indoor environments limiting the usage of processes with industrial robots on construction sites. Here, the sky factory approach was introduced to ease the integration of industrial robots by changing the working environment into a factory-like setting [10], which, however, can be applied only to a limited extent on a construction site due to its high cost and complexity.

The idea of automating the deconstruction process with new emerging technology has drawn the attention of many researchers. Recently, the researchers developed a selective deconstruction method based on electrodes generating electro-pulses for removing and cutting concretes, which mainly aims at the mining industry [11]. However, the additional safety issues and scalability still remain open.

3 Robot-Assisted Deconstruction Approach

This study introduces an alternate deconstruction strategy that attempts to offer an example of a practical solution for the controlled deconstruction of concrete walls which is developed at the conceptual level in this work.

This work aims to develop a robot-assisted deconstruction process, which minimizes human risks and maximizes efficiency and accuracy by utilizing robot technology. To achieve this goal, three main subsystems are to be considered:

Subsystem 1: Robotic system for cutting tasks. In order to increase the level of task automation, the corresponding level of machine autonomy is first considered. Here, the development goal is that the robotic system perceives the environment, considers its hardware capability, and considers the input from the human operator (i.e., the desired geometry of the cut element) to generate the appropriate motions automatically.

Subsystem 2: Vision System. As the overall goal is to minimize human risks and automate the deconstruction process, the information from the environment has to be collected and transferred to the

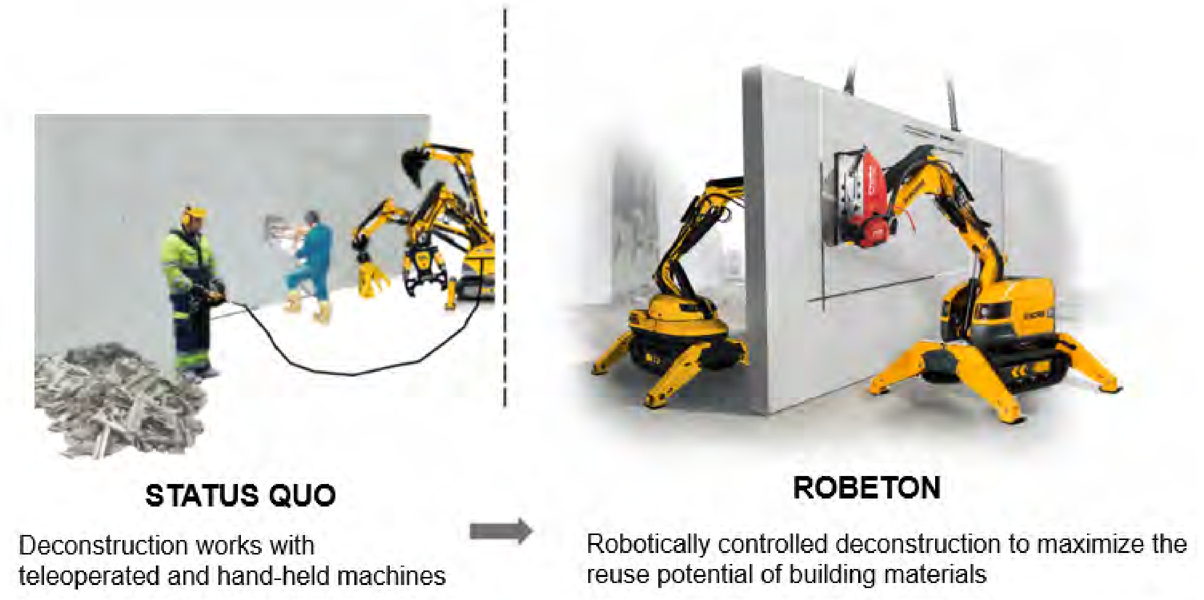


Figure 3. The overall vision of this work is to maximize the reuse potential by increasing the level of autonomy in deconstruction tasks.

robotic system. By collecting the visual feedback from the remote working place, one can improve the telepresence of the operators and avoid the scenarios where the operators have to be present on the construction sites.

Subsystem 3: Robotic system for stabilizing the cutting process and holding the cut elements. While the first robotic system is responsible for automatic cutting, this other robot supports the first robot so that the element that is being cut does not swing back and forth and collides with the environment during and after the cutting process.

3.1 Deconstruction Robot

The first subsystem focuses on the automated, exact cutting of concrete walls, which is one of main difficulties connected to controlled deconstrucion. Currently, teleoperated hydraulic machines are commonly used for this task. However, the operation is difficult even for experienced operators since many joints of the machine must be manipulated simultanesouly with joysticks.

In this work, we aim to increase the autonomy level of an existing teleoperated hydraulic deconstruction machine rather than developing a new deconstruction robot from the scratch, as it offers various benefits:

1. Deconstruction of concrete walls is a heavy-payload process. The machinery used for the process must be very dependable, durable, and resistant to force. Hydraulic machines are a better fit in this situation than electric machines, such as industrial robots, which have a limited payload and are generally error-prone in outside conditions (dirt, humidity, etc.).
2. The robustness of the selected hydraulic machine has been proven in different disaster places [12]. The system can drive on non-flat or soft ground and can perform different tasks by changing the end-effector.
3. The commands for the control system and the actuators are already interacting using electrical signals since the system is teleoperated. The whole system does not need to be electrified in order to increase the level of autonomy.

The deconstruction machine's precise motion control is critical as it determines whether the deconstructed material can be directly reused without losing its intrinsic value or has to be recycled through down- and upcycling. In our previous work [13], we investigated the possibility of converting the teleoperated hydraulic machine BROKK 170 into a programable robot that can be controlled by a motion controller implemented on an onboard computer. As most teleoperated hydraulic machines just like BROKK 170 are not equipped with any motion sensors that can estimate the disparity between actual and commanded motion. Thus, motion sensors such encoders were added to the machine. Then, a communication link between an onboard computer and the machine was built by analyzing

Figure 4. Snapshots of the BROKK 170 tracking a trajectory in the TCP-level. The grey tool can be interactively positioned and rotated by the operator defining the desired tool pose. According to the desired tool pose, a TCP trajectory and the corresponding joint trajectories (upper row) are generated. The joint trajectories' joint angle changes are then converted into the PWM signals to move each actuator along the desired joint trajectory (lower row).

the communication between the original input device and the machine. Based on this result, a general CLIK technique was used to convert the desired motion descriptors represented in task space to corresponding joint motions. The joint motions were then converted to CAN bus messages, which generated the corresponding PWM signals for the valve system. Instead of controlling each axis independently with the joystick, the suggested technique allowed the teleoperated machine to be programmed in task space. In the previous work, the resulting accuracy was 2 *cm* for the position and 0.015 *rad* for a point-to-point movement. Due to the nonlinearities in the hydraulic system, the error in Root Mean Square Error(RMSE) while tracking TCP path was relatively larger with 6 *cm* in the TCP space.

The current system setup interacts with the operator using an interactive tool, as the snapshots of Fig. 4 visualizes. The operator defines the higher-level command, i.e., desired tool pose at the task level. The corresponding joint trajectories are generated using the Robot Operating System (ROS) environment [14] and the related motion planning framework, MoveIt! [15] to generate a collision-free motion by fulfilling the pre-defined requirements such as the step size and the goal time. To allow the command from the operator, as depicted in Fig. 4, the operator has to be aware of the local circumstances of the remote environment, i.e., the geometry of the target object. Here, we deploy another robotic platform capable of providing the visual feedback of the remote workplace from different viewpoints according to the operator's input.

3.2 Vision System

Typical control stations incorporate numerous 2D camera views from various viewpoints to boost telepresence by presenting the gathered sensory data to a remote location. Such techniques, on the other hand, have been found to be troublesome in terms of the operator's fragmented attention and overloaded network.

This work uses a mobile robot with a depth camera to capture the remote working scene in a 3D point cloud and transmit it to the operator and the robot. Especially, the 3D visualizing technique has shown its effectiveness in improving the telepresence and operator's manipulation capabilities in different works [16] [17]. The geometrical information collected in 3D will be used together with normal 2D camera images to increase the operator's telepresence and maximize the understanding within remote environments.

The mobile robot used in this work is based on a commercially available platform from Innok Robotics. It is further equipped with a 3D depth camera to provide 3D visual feedback from an arbitrary viewpoint of the remote workplace. Additionally, it is equipped with different sensors such as an inertial measurement unit (IMU) *Xsens MTi-30-2A8G4* and a 2D laser scanner *Sick micro Scan 3* which will be utilized for localization tasks on construction sites.

3.3 Supporting System

The cutting process has to be stabilized by an additional system. The concrete walls often weigh up to multiple tons and are often up to several meters long. When the cutting process is halfway done and the cut element is partially dissolved from the wall, there is the risk that the element can fall down on the robots or the ground. To prevent this risk, we utilize a supporting system that consists of two different machines with distinct purposes:

- **Additional hydrualic robot**: Additional robot will be mainly used on the other side of the cut element

Figure 5. Conceptual visualization of the planned usecase: Top-down deconstruction approach with tower crane

to prevent the swing that might be generated when the element is dissolved from the wall. Thus, it is essential to estimate the forces applied by the first deconstruction robot to compensate them. Here, the communication between these multiple systems will be enabled in the ROS environment.

- **Tower crane**: In this case, the crane is used to compensate for the heavyweight of the cut element during the process and carries it to the temporary storage point after cutting is finished.

4 Demonstrator

The major goal of this project is to enable robotically controlled deconstruction, which will maximize the reusability of building materials. The envisaged demonstrator involves the following steps: (i) 3D point cloud methods for visualizing the remote scene to the operator and extracting useful visual features to support for decision making, (ii) Adaptive robotic path planning considering the local information such as the geometry of the concrete wall and the input from the human operator, (iii) Development of suitable end-effectors for cutting the concrete walls into directly reusable pieces.

Here, the experimental setup will be installed on the reference construction site on Aachen Campus West. The robotic system described in the previous sections will be evaluated within the scope of the scenario (see Fig. 5).

4.1 Top-down deconstruction approach with tower crane

The test scenario will demonstrate how the envisioned robotic technologies can be applied to the adaptive reuse of concrete walls. The top of the structure is presumed to have been removed at this point, as visualized in Fig. 5.

First, the demolished wall structure will be captured in 3D, and the acquired data will be communicated to the operator over the on-site wireless network. The deconstruction and support robots will then be teleoperated and placed in front of the wall. It's worth mentioning that the robot's autonomous driving isn't covered in this research. The ideal position for the robot to reach and handle the wall will be determined and shown to the operator based on the acquired geometric information of the wall. The operator defines the required geometry for the cut element after the robots are in place. An adaptive tool-path trajectory is developed based on this input and the gathered 3D knowledge about the wall structure. The deconstruction robot's low-level controller then accurately executes the generated trajectory. The tower crane is mostly utilized in this scenario to stabilize and transport the cut part to a temporary storage location.

4.2 System requirement for the selected application area

This section briefly describes the necessary system requirement that the envisaged robotic system described in the previous section has to fulfill. Although our previous research [13] about the deconstruction robot is rather primitive and leaves further questions, for instance, in terms of accuracy, the technical findings are used in this section to build the bottom line of the development direction.

4.2.1 Reuse of concrete elements

The potential of reusing construction components has been intensively analyzed in the project Superlokal in Kerkrade [18]. Four high-rise concrete buildings located in Kerkrade were deconstructed, renovated, recycled and reused as experimental attempts to analyze the potentials of the materials from the old housing. One of the subproject was aimed at the reuse of the harvested material into a new building. The concrete blocks as main body, the concrete staircase, the kitchen core, the paving material, the wood doors and windows, the aluminium handrails and so on were all reused without post-processing and have made up to 95% of the overall building materials. Especially, the idea of reusing mineral materials such as concrete which makes up to 80% of the total CDW waste stream has the potential to dramatically contribute to the sustainability in the construction industry.

Table 1. Indicators for the performance assessment

	Indicator
Automated cutting process	Improvement of the accuracy of the cutting tasks
	Reduces the time required for the cutting tasks
	Reduces the number of human workers working on-site for the cutting tasks
	Workers feel more safer during the cutting tasks
Cost	Additional costs for extra machines/ hardware
	Reduced time/costs
	Increased work productivity
Sustainability	Savings of the grey energy
	Material savings/ increased resource reuse rate

Table 2. Evaluation of the tracking in the TCP-level

	PTP Movement	TCP-Trajectory Tracking
Current RMSE	2 cm	6 cm
Goal RMSE (DIN 18202)	1.2 cm	1.2 cm

However, the manual process of measurement, positioning, machines operation and removal of toxic substances has increased the required efforts and the complexity to the project. As a result, the need for automated technology to compensate for inefficiency and safety issues throughout the deconstruction process has been established.

Certain technical tolerances, such as cut precision, must be ensured during the automated deconstruction process to maximize the reuse potential of cut elements. Here, we refer to the regulations of DIN 18202 [19], which describe permissible tolerances for the manufacture of components and the execution of structures in building construction: For a structural component, i.e., a wall with a length of 3 m, the deviation must not exceed 12mm.

As stated in Sec. 3.1 and summarized in Table 2, the current error in PTP-movement and tracking TCP-trajectory lies in 2 *cm* and 6 *cm*, respectively, whereas the allowed deviation in material processing lies in 12 *mm*. Thus, the first step to deploying the planned deconstruction robotic system in the actual process is the precise motion control of the hydraulic manipulator. However, as the nonlinearities in the hydraulic system greatly affect the high-precision control, further research is required in this direction.

4.3 Usecase Assessment

The increase of reusable concrete material due to automated deconstruction controlled cutting process will be assessed and compared to regular procedures. Primarily, the demonstrator will be evaluated by the following indicator categories: (i) Automated cutting process, (ii) Cost, and (iii) Sustainability.

As the primary goal of this work lies in improving the autonomy level of the cutting task, the new robotically controlled deconstruction approach will be compared with the existing deconstruction/demolition approaches to demonstrate the improved accuracy, significant reduction energy, and human resources consumed for cutting tasks. Besides improving cutting tasks, productivity and worker safety on-site will also be evaluated as one of the major constraints for automated deconstruction is usually the cost. The financial aspect, i.e., the economic viability of this new robotic approach, will be investigated. Finally, the ecological viability, increased reuse potential, corresponding material savings, and related grey energy will be investigated.

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6 Conclusion

Automated deconstruction will remain the main research topic in the following decades due to the constantly rising demand for sustainability and the permanent shortage of skilled workers. In line with this issue, this work investigated the current limitation of existing methods and identified the lack of automated solutions for deconstructing concretes. Given this result, this work presented a conceptual approach with different subsystems for the robot-assisted on-site deconstruction process. Next, the challenges that might arise from deploying and using the robotic systems on the construction sites and the corresponding demonstrator for further investigation were jointly analyzed and introduced. Finally, possible assessments to effectively evaluate the planned demonstrators were defined.

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