REVIEW

Bots2ReC: introducing mobile robotic units on construction sites for asbestos rehabilitation

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Received: 9 January 2017 / Accepted: 1 August 2017 / Published online: 10 October 2017
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Abstract The “Robots to Re-Construction” Bots2ReC project was launched in 02/2016 to introduce mobile robotic units on construction sites for the automated removal of asbestos contamination. The novel use case of asbestos removal and the dedicated robotic system are introduced. After giving the motivation for the use case, a brief overview of recent approaches to mobile robotic systems on construction sites is given. Analysis of the use case and the situation of asbestos contamination in Europe follow. The project approach is shown, and specific challenges regarding mobility, perception, and collaboration are analyzed. The publication concludes with a brief description of the current prototype and an introduction of the project consortium. As we are addressing the first special edition of this journal, our focus is on the introduction of the use case, challenges, and approach rather than on specific scientific or technological solutions, that will follow during the course of the project. <http://www.bots2rec.eu>.

Keywords Construction robotics · Asbestos · Rehabilitation · Mobile robotics · Construction industry

1 Introduction and motivation

Currently, automation, especially robot-based automation, is not prevalent in the domain of construction and demolition industry. Most of the tasks in this domain are based on manual operation supported by machineries, such as hoists and cranes or by hand-held tools, which often are of considerable weight and which expose the worker to high levels of dust, noise, and vibration. One major market sector in the construction and demolition industry is the clearance and refurbishment of buildings contaminated with asbestos, so called rehabilitation sites. Every exposure to asbestos fibers is highly hazardous to humans causing serious health hazards like asbestosis and cancer. Worldwide, 90,000 deaths are assumed to be caused by asbestos exposure each year. Therefore, intense safety measures have to be taken to reduce the health risks for employees. The prevention of the exposure to asbestos fibers by automation of the process will sustainably help to protect the health and physical integrity of construction workers in Europe and worldwide.

Due to the very inefficient or even prohibited manual performance of asbestos removal, asbestos is too often covered or encapsulated instead of being removed. Keeping the current rate of refurbishment, it can be estimated that the clearance of all buildings in Europe would need 500 years and holds the great danger of asbestos exposure to humans in the future. The fire in the port of Roermond (The Netherlands) in December 2014 has shown the consequences dramatically: For 2 days, the contaminated downtown had to be evacuated, and the risk and health impact to the public are not known.¹ The automation of the

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¹ <http://www.dutchnews.nl/news/archives/2014/12/roermond-centre-closed-off-after-massive-fire-releases-asbestos/>.

process would allow the decomposition and clearance industry in Europe to operate more efficiently and increase the economic competitiveness: High costs would no longer prevent refurbishment. Motivated by the demand of new solutions for this market sector, the consortium initiated the Bots2ReC project with the aim of:

“Introducing, testing and validating an operational process for the automated removal of asbestos contamination at a real world rehabilitation site using a robotic system.”

Even though automation solutions are not yet widely present on construction sites, state-of-the-art technology and knowledge are already available from other domains, such as industrial production, mobile navigation, light-weight robotics, and modern sensor systems. Recent approaches show a huge interest in the implementation of mobile robotics on construction sites.

Tele-operated mobile manipulators, such as the Meyco ME concrete spraying robot (Atlas Copco: Meyco Concrete Spraying and Brocure 2016) or the Brokk 50 demolition robot,² are designed and used for high payload tasks. Available systems with hydraulic actuation and skid steering systems, however, have limited applicability because of their systems weight and footprint. They cannot be used inside standard buildings. Specifically for asbestos decontamination, the French subsidiary of Brokk introduced a compliantly suspended abrasive tool attached to a long reach slider³ to enlarge the workspace of the tele-operated manipulators.

Different approaches aim at introducing more autonomy to robotic systems on construction sites. Roby is a pilot project from 2006, designed for the automatic drilling of holes into the facade of large buildings and civil work structures.⁴ It is composed of a high payload omnidirectional platform and industrial robot with a total weight of 3 tons, guided by laser and camera sensor technology.

These and other tele-operated systems are available for construction robotics, but not targeted to the asbestos removal workflow that, for example, needs to consider the seclusion of the site. Many pilot studies in the past did not succeed with a market relevant project follow-up.

nLink⁵ released a commercially available mobile drilling robot in 2015. It can drill holes to the ceiling based on the building information files, and guided by cameras and laser positioning systems. By choosing a rather small mobile platform with a telescopic vertical axis and a lightweight robotic arm, indoor use is now possible with

such a structure. Based on a similar kinematic structure, an asbestos removal robot was developed in Japan in 2010 (Arai and Hoshino 2010). Using a metal brush, asbestos coating is removed from metal beams after manual programming of the robotic system. The test performed states the feasibility of the approach; however, as a conclusion, the efficiency and operational speed need to be increased, for example, by introducing a higher degree of autonomy, and reducing the programming and ramp-up efforts. Furthermore, the system is not suitable for larger areas as targeted in the Bots2ReC project.

Eco Amiante⁶ successfully implemented an omnidirectional mobile platform equipped with an abrasive tool and external aspiration to remove material from the floor. It is programmed semi-automatically, following pre-defined patterns. As a conclusion, it can be said that there are different approaches to introduce mobile robotic systems on construction sites. However, different practical limitations still hinder the extensive use of autonomous systems.

The Bots2ReC project combines the expertise in the domain of construction and demolition industry with state-of-the-art technology in robotics and sensor technology to automate the difficult and dangerous tasks of asbestos removal. The combination of the knowledge and expertise from the involved partners allows introducing a robotic solution to the usually unstructured and unpredictable environment of the domain of construction and demolition industry. Using robots for asbestos removal protects workers from hazardous environments, and simultaneously increases the productivity and lowers the production costs. In the targeted use case of automated asbestos removal, the environment is semi-structured after the initial preparation of the rehabilitation site as described in the following.

2 Use case and scenario

For the introduced use case, small to mid-sized rooms and corridors (e.g. in a private flat or an office) are targeted as a typical site for the clearance and refurbishment from asbestos material. On such a site, asbestos contamination is present as a component in various material mixtures, among others, such as in ceramic tiles, in glue, in plastering, as spattling compound, paint and heat, and fire protective coating. It is used on walls, ceilings, and floors. These forms of asbestos contamination represent 15–20% of the global asbestos quantity, and the resulting market of clearance and refurbishment accounts for several billion Euros (see Sect. 3).

According to our investigations, the most common forms of asbestos contamination inside private flats are:

² <http://www.brokk.com/us/50/>.

³ <http://www.constructioncayola.com/environnement/article/2016/09/23/107668/pmp250-ponceuse-amiante-brokk-made-france.php>.

⁴ <http://www.industrie-techno.com/robby-l-hybride.32712>.

⁵ <https://www.nlink.no/>.

⁶ <http://www.eco-amiante.fr/>.

Wall plaster (for 1 flat out of 4)
Plastic floor covering (for 1 flat out of 4)
Plaster on ceilings (for 1 flat out of 7)
Wall ceramic tiles (for 1 flat out of 7).

This is market targeted in the Bots2ReC project. More than 75% of the asbestos in buildings is incorporated in hard materials, such as asbestos-cement (e.g. Eternit) or structural panels. The removal of this sort of asbestos is not targeted in the project, as the clearance procedure, machinery, tools, containment, and costs vary significantly from the robotics use case described below.

Besides the removal of asbestos itself, three supporting-tasks are performed manually by according specialists during the clearance and refurbishment: the mapping of contaminated material, the containment of the site, and the disposal of waste. Based on specialists' experience, specimens are taken manually from potentially contaminated material and analyzed chemically to map the asbestos contamination. The containment of a site before the removal of asbestos separates the contaminated and hazardous areas from the environment and general public. The site is cleared from all non-permanent items and concealed using specialized robust plastic foil and gluing tape. Areas that will not be processed are covered (see Fig. 1).

The disposal of waste follows the standard procedures already established in the building and construction industry. Aspired particles and dust are stored in specific containment bags and removed from the site manually (Fig. 2).

The removal of asbestos material can be clustered into different asbestos removal tasks: Different surfaces, materials, and structures are usually contaminated on the site and need to be cleared from asbestos. Most of the asbestos removal tasks need to be performed with abrasive or destructive tools like grinding disks or scarification cutter. The extensive personal safety equipment to be used

Fig. 1 Examples for the containment of sites before the removal of asbestos

Fig. 2 Workflow during clearance and refurbishment of a site from asbestos contamination

makes the manual performance very inefficient. Accompanied by the supporting-tasks, the removal of asbestos material on the site can be automated efficiently for specific tasks: Flat walls, ceiling, and floor are easily accessible and of easy geometry and, consequently, the automation can be performed in a robust and reliable way. Contaminated ceramic tiles, plaster, fillers, and wall paint occur in majority of the analyzed sites. Contaminated ceramic tiles, plaster, fillers, and wall paint occur in a majority of the sites analyzed. Concentrating on the most commonly used material and removal tasks will make the automation efficient. Therefore, the following set of tasks is covered within the Bots2ReC project:

- Disk grinding for removal of plastering, spattling compound or paint from walls, floor, and ceilings
- Surface scarification or grinding for removal of the ceramic tiles from walls
- Disk grinding for removal of the glue after the removal of ceramic tiles
- Surface scarification or grinding for removal of floor covering.

Further disk grinding and surface scarification operations will be exploited during the project. More complex tasks, such as the asbestos removal from pipes, structural steel works, and highly complex surfaces, will not be automated. Given the current state-of-the-art, automation is more complex for these tasks, but field tests at the end of the project will give an outlook to the risks and chances towards widening the robotic automation for these much more demanding tasks.

3 Asbestos contamination in Europe

In preparation of the Bots2ReC project, the situation of asbestos contamination in Europe was investigated. The results are summed up in the following.

Evaluating the quantity of asbestos present in European buildings is difficult due to the inhomogeneous and incomplete documentation in different countries. The situation is documented well for France and there are few legal dispositions or studies focused for certain other countries. The asbestos consumption in the last century (as shown in Fig. 3) can be evaluated to compare information and estimations. The Audencia Junior Conseil investigated the European asbestos market in a comprehensive study (Audencia Junior Conseil: Étude du marché du désami-antage en Europe, Study commissioned by Bouygues Construction, March 2015), and the main findings are summed up in the following.

In France, according to a publication from Union Sociale pour l'Habitat (L' Union Sociale pour l'Habitat: Amiante 2014), more than 40% of the housing stock is contaminated by asbestos (15 million flats), indoor or outside (façades or roof) or in technical installations. An important study of the Centre Scientifique et Technique du Bâtiment, in 2005 (Chaventré and Cochet 2005), confirms these figures and shows that for non-residential buildings 2 million out of 3.6 million buildings are affected. More than 4 million tons of asbestos were imported in France during the twentieth century (Association Nationale de Défense des Victimes de l'Amiante: Amiante et Economie: Importations, coûts [France] 2011). Only uncertain approximations are available for Great Britain, but estimations predict a total of 4.4 million buildings that might need asbestos removal, a quite low figure compared to France. It does probably not include the amount of already enclosed asbestos which is still present in “treated” buildings. We can notice that in Great Britain, the amount of imported asbestos exceeded 3 million tons during the

last century. It is not so different from the French amounts, and also comparable to Spanish figures which raise 2.6 million tons. The German situation can be estimated to be similar, according to the apparent consumption of asbestos. In Italy, some studies announce very high amounts between 30 and 40 million tons of asbestos. It must be considered that Italy was a great provider of asbestos-cement (with Eternit) and these figures may include also a part of other countries as “clients”. The only Italian region, where figures are available for asbestos contamination, the Toscana, announces 2.5 million tons of asbestos just for its territory. For Belgium, it was estimated that 800,000 tons of asbestos were present in 2001. In Hungary, an isolated study of the NIOH detected presence of asbestos in 500 buildings of Budapest. These figures from various European countries prove that asbestos contamination is present in millions of flats all over Europe, even if exact figures are scarce.

The asbestos consumption in the European Community in 1973 (when major amounts of asbestos were used) indicates that, in Western Europe, the main countries probably present similar quantities of asbestos as France, where the figures are well known.

Few studies allow estimating the global costs of necessary refurbishment and clearance procedure for the European market. Based on the estimated refurbishment costs for the French market, a total amount of 80 billion Euros (L' Union Sociale pour l'Habitat: Amiante 2014) to 200 billion Euros (Le Figaro 2014) can be expected for private housing. For France, 15 billion Euros is needed to clean the polluted social housings only (Guerin and Jouan 2014). Taking into account private housings and the non-residential sector, the total amount would exceed 100 billion Euros. In Great Britain, the estimated costs are much lower: 15 billion Euros are estimated for all buildings. It is worth mentioning that in Great Britain, asbestos treatment means to keep the pollution in place and cover it with some protection. This is far less expensive and partly already done, which can explain the difference in the estimation compared to France. Based on the data presented above, it can be estimated that the five to six biggest countries in Western Europe are in a situation similar to France. Even if the cost of asbestos removal can be reduced in future, it can be estimated that the total market of asbestos removal exceeds several 100 billion Euros for these countries only.

Fig. 3 Apparent asbestos consumption in Europe in the last century based on the national production, imports and exports

4 Project and development approach

The Bots2ReC consortium developed a first version prototype, based on the general requirements of the construction and demolition industry, and the specific requirements of the robotics use case described above. Using this first version prototype (see Fig. 5) allows us to

develop the process of automated removal of asbestos contamination and the according process control systems in several iterations.

A testing rehabilitation site (see Fig. 7), representing realistic conditions as analyzed for the use case, is available and will be used during the development and testing phase. The ongoing developments, and updated technical requirements and specifications will lead to the design and realization of a second version of the robotic system with two robotic units.

This final prototype will be used for further developments and the final demonstrations and benchmarking. The final version of the operational process and robotic system will be demonstrated and benchmarked under real world conditions in 2019. The complete workflow, including the mapping of contaminated material, the containment of the site, the removal of asbestos, and the disposal of waste will be executed in contaminated flats, representing typical rehabilitation sites. The final target is the demonstration of an automated asbestos removal process that is at least as efficient as manual operation and does reduce manual work in hazardous environments. The main benchmarks are the time to completion for the overall process and the need of manual intervention by the operators, both decisive for the economic success of the robotic solution. An important aspect considering this benchmark is the uninterrupted operation that is possible with robotic systems. The very short 2-h shift for workers due to safety regulations can be omitted. The project follow-up aims at the exploitation of

the project results with a process and system, reaching market maturity shortly after the end of the project.

The targeted robotic system at the project end as sketched in Fig. 4 will consist of multiple mobile robotic units that perform some tasks autonomously. Each unit consists of a mobile platform and a robotic arm with an abrasive tool. The combination of optical and radar sensor systems allows the environmental perception and local monitoring of the asbestos removal tasks. Supported by a user interface, the operator can select different areas on a virtual representation of the rehabilitation site and assign asbestos removal tasks that will be executed autonomously. The user interface allows the permanent supervision of the automated process and optional remote control. The robotic units and tools will be sealed and covered with removable gaskets, where sealing is not feasible. At the end of the operational process, they are cleaned and decontaminated manually. In the following sections, some specific challenges for the described use case and the design of the first version prototype are described.

5 Specific challenges within the project

The introduced use case leads to a set of specific challenges and requirements for the robotic system. In the next paragraphs, some exemplary requirements are introduced briefly to give an insight to the demanding project scenario.

Fig. 4 Sketch of the real world rehabilitation site with two robotic units during the automated removal of asbestos contamination

Fig. 5 Early prototype design

5.1 Mobility

In contrast to the scenario sketched in Fig. 4, the available space in private flats or offices might be limited in small rooms and corridors. Neighboring corridors of 700 and 800 mm width are most common (80–90% meet this specification or are wider) and are considered as the reference defining the limitations for the footprint of the robotic system. This limits the dimensions of the mobile platform to a width of 600 mm, a length of 800 mm, and a maximum height of 1800 mm.

At the same time, the robotic units need to be able to remove asbestos from the floor, the walls, and ceilings with a height between 2.10 and 3.0 m.

The requirements for a limited footprint and a wide/high workspace are difficult to combine in the same design. The mass repartition and dynamic forces have also to be considered into the design and control of the robotic unit, so that a sufficient stability margin on the supporting polygon can be maintained. During the design phase, the limited footprint and height are a major restriction for integrating all the required components. The arm architecture is evaluated by comparing the range of motion and space for different positions of 6 DoF articulated arms, with and without vertical slider (Fig. 6). These iterative investigations lead to a kinematically redundant system with 7 dof. The redundancy allows a large vertical workspace due to the slider mechanism in combination with relatively compact space requirements.

The platform design is mainly based on the traction system; The 300 kg platform needs to be manoeuvred on a 125-micron polyethylene film used for the seclusion of the site. Different kinematic configurations (differential drives,

Fig. 6 Work space analysis for the operation in narrow corridors

and swerve-, double-swerve-, castor-, and omni-wheels) were tested in various scenarios. These tests led to the combination of a differential drive-suspended central axle in combination with four supporting omni-wheels in the corners that can stabilize the robot and avoid slipping on the plastic foil for preserving seclusion.

5.2 Perception

A precise and reliable map of the whole removal area is essential for the process. On one hand, this map has to be suitable for the navigation of the mobile unit. On the other hand, this map is necessary for the positioning of the robotic arm and tool in order to perform the removal task. Given regular visibility, suitable maps can be obtained using conventional laser- and vision-based perception; a two-dimensional map for navigation and a three dimensional semantic map for task selection and fulfilment. The underlying Simultaneous Localization and Mapping (SLAM) algorithms are well known and to some extent considered as solved (Cadena et al. 2016).

But as visibility might be reduced by dust resulting from asbestos removal, novel perception approaches are required in the scope of the Bots2ReC scenario. As already proposed in literature, but with different hardware and in other contexts (Adams and Jose 2012; Rouveure et al. 2016), our proposed solution is to use a recently developed compact 360° Frequency Modulated Continuous Wave (FMCW) radar sensor in addition to the conventional lidar sensors. As radar waves are longer compared to laser waves, dust particles can easily be passed, enabling robust, yet less accurate, perception. Besides varying wavelengths, one important difference between radar and LIDAR sensing is the output of the sensors; in contrast to LIDAR sensors, radar sensors give access not only to a point cloud of distinct range measurements, but to complete power versus range spectra (Mullane

2010). This raw data contain lot more information and can be processed in different ways. First results show that it is basically possible to perform SLAM with the aforementioned FMCW radar sensor. Nevertheless, the remaining challenges are to handle the raw data of the radar sensors in an efficient way and to enable high accuracy as well as real time computation. As a consequence existing SLAM algorithms have to be modified and most likely new algorithms must be developed. Finally, the two-dimensional map obtained through radar sensing needs to be fused with the initial maps obtained through laser- and vision-based perception, enabling robust navigation and task fulfilment in arbitrary visibility conditions.

5.3 Collaboration

Although human is not present in the workspace of the robot (as generally considered in human–robot collaboration), human–robot interaction must be considered when designing the control interface. It must combine remote control and allow a certain degree of autonomy of the robot for large surface cleaning, while keeping interaction with the supervisor in case of problems or for cleaning more complex areas. Furthermore, the collaboration of multiple robotic units must be possible for future developments.

The core piece for collaboration can be found in the central process control system (CPCS) of the robotic system developed in this project. It provides the interface for the human supervisor via a graphical front-end and translates the defined tasks into robotic related commands afterwards. A special challenge is the trajectory planning during the removal process because the process parameters (e.g. processing time) cannot be determined exactly.

The solution for this dynamic planning needs to be found during the Bots2ReC project within the phase for the second prototype.

Beside this task for enabling autonomous movements, it is a core concept of Bots2ReC to allow dynamical and intuitive task definitions by the human user. As shown in Fig. 7, the approach is to provide a semantic map for the user via the graphical front-end of the CPCS.

The user can interact with the map by selecting parts of the walls, excluding non-removal areas and defining tasks for removal surfaces. Different tasks, such as *removing paint* or *removing tiles*, are pre-defined and can be mapped onto selected surfaces of walls, ceilings, and floors. Beside the task definition and the virtual 3D representation, the user interface also provides information about the robotic hardware state, several video input panels, and a guideline through the different modes of the robotic system. Out of this, the user interface follows the aim of simplifying the task definition to a minimum and allows further extensions as, e.g. the import of building information modeling data in the near future.

6 Current state and first prototype

Specific requirements and careful design considerations led to a number of individual components and adaptations implemented in the first version prototype (see Fig. 7). Especially the size ratio of all components demands careful integration. As many process parameters and detailed solutions for the process are unknown at the current state, the first version prototype is designed to be an early development and testing platform, rather than a close to

Fig. 7 Current design for the first version prototype and user interface

Fig. 8 Passive compliant tool guidance and first results of the material removal

market solution. The manual mechanical stabilizers allow for safe and stable grinding by enlarging the support polygon of the platform itself. Furthermore, force sensors provide data for online stability analysis of the process.

A standard industrial abrasive handheld tool is integrated with a force sensor (see Fig. 7), to be able to analyze the process forces and also use them as control input. The removal process is executed by grinding the material (e.g. plaster as shown in Fig. 7) and aspirating the resulting dust. A set of control scenarios with increasing complexity is being investigated.

In the first approach, the standard tool is controlled in position to judge the suitability of the tool and hardware. Material can be removed, but the position control without external sensor technology is very challenging for a robust process.

The approach shown in Fig. 8 is based on a mechanical compliance of the tool guidance with castor wheels. The mechanical compliance includes two parts: A linear slider and spring compensate position tolerances of the robotic arm; a universal joint compensates orientation tolerances. A second set of springs is used to exert a constant force to the tool. In the first test, this approach has shown very promising results and a smooth material removal. A major drawback of this approach is the reduced working area of the tool at the wall. Therefore, design improvements are considered, and more complex control approaches like the position and force control with sensor feedback will be implemented and investigated.

Deviating from the original scenario, the aspiration and filtering units are integrated to the mobile platform. The

necessary diameter of the aspiration pipe prohibits the use of a cable reel. Its dimensions would exceed the space requirements.

7 Conclusion and future work

The Bots2ReC project has the ambition to develop collaborative mobile manipulating robots capable to perform safe asbestos removal in tele-operated and partially autonomous modes. A prototype has been developed, including: a non overconstrained suspended mobile base with six wheels, differential steering, and no slip on the ground, thus preserving the plastic foil used for seclusion; a 7 DoF redundant manipulating arm capable to reach a ceiling at 3 m and supporting a grinding tool on a compliance; other components, such as an aspiration unit and a cable reel organized in a very compact setting, compatible with constraints, such as passing through doors and steering in narrow corridors.

The Bots2ReC project started in February 2016. The shown prototype has been put to service in March 2017 and the testing program started in May 2017. Intensive tests and an ongoing development of the software and central process control system will lead to the second version prototype, specifically designed for the developed asbestos removal process. Beside the described tests on the tool and arm control architecture, the overall system is being improved and developed further with a particular focus to the end user needs and the fulfilment of the overall process, rather than the grinding process alone. The consortium welcomes any input from professionals in this field and invites the interested reader to join our advisory board. Information can be found on the project website <http://www.bots2rec.eu>.

7.1 Project consortium

The use case is driven by the industrial end user Bouygues Construction, responsible for the clearance and refurbishment of a site and operating the system.

Robotnik Automation SLL develops and manufactures mobile platforms and manipulators for service robotics applications and unmanned ground vehicles.

Telerobot Labs Srl offers high level competences in design, development, and production of robotic and mechatronic devices and will develop the robotic arm and tools.

indurad is a producer and integrator of optical and radar sensor technology with a unique data processing and visualization software framework.

The robotic system including the developed operational process for the use case is integrated by the Fundacio eurecat, an experienced system integrator.

The state-of-the-art technology in the areas of control, task planning and sensor data processing will be augmented by the research institution RWTH Aachen University.

SIGMA Clermont brings research expertise in mechatronic design, modelling, perception, and collaborative control for simulating and piloting the robotic system in its environment.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under Grant agreement no. 687593.

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