Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 11 (2017) 389 – 396

Procedia MANUFACTURING

27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy

Towards intelligent autonomous sorting of unclassified nuclear wastes

Andrea Basso[a], Václav Hlaváč[b], Jiří Hůlka[c], Michael Jilich[d], Pavel Krsek[b], Sotiris Malassiotis[e], Rezia Molfino[d], Vladimír Smutný[b], Libor Wagner[b], Matteo Zoppi[d] *

a Ansaldo NES Ltd., Spring Road, Ettingshall, Wolverhampton,WV4 6JX, United Kingdom
b Czech Technical University, Czech Institute of Informatics, Robotics and Cybernetics, 166 66 Prague 6, Zikova 4, Czech Republic
c National Radiation Protection Institute, 140 00 Prague 4, Bartoškova 28, Czech Republic
d Universita degli Studi Di Genova, Dept. of Mechanics and Machine Design, 16145 Genova, Via Opera Pia 15A, Italy
e Center for Research and Technology Hellas, Information Technologies Institute, 6th km Xarilaou - Thermi, 57001 Thessaloniki, Greece

Abstract

Sorting of old and mixed nuclear waste is an essential process in nuclear decommissioning operations. The main bottleneck is manual picking and separation of the materials using remotely operated arms, which is slow and error prone especially with small items. Automation of the process is therefore desirable. In the framework of the newly funded European project ECHORD++, experiment RadioRoSo, a pilot robotic cell is being developed and validated against industrial requirements on a range of sorting tasks. Industrial robots, custom gripper, vision feedback and new manipulation skills will be developed. This paper presents application context, cell layout and sorting approach.

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing

Keywords: nuclear waste sorting, robotic manipulation, machine vision.

* Corresponding author. Tel.: +39-010-353-2837; fax: +39-010-353-2298.
E-mail address: zoppi@dimec.unige.it

Peer-review under responsibility of the scientific committee of the 27th International Conference on Flexible Automation and Intelligent Manufacturing
doi:10.1016/j.promfg.2017.07.122

1. Introduction

The scope of the 18 months RadioRoSo experiment [1] running under the umbrella of EU FP7 project ECHORD++ [2] is decommissioning operations performed in nuclear waste storage facilities. First, a significant amount of old and undocumented nuclear waste is buried in silos in shallow underground, in unused mines or other facilities in several countries. Many of these facilities, created as far as 60 years ago, pose a safety and environmental risk. Several countries have started or considering the decommissioning of these wastes in safer facilities. Second, decommissioning of nuclear power plants is also a significant emerging problem. It is expected that across Europe up to 80 nuclear power reactors will close down the next ten years, and then they will be decommissioned.

Decommissioning is a complex and expensive process, in which the problems of handling contaminated heterogeneous waste materials play a fundamental role. For example, the decommissioning of storage facilities in the UK is a multi-billion €project expected to run for 10 years.

In the storage facilities, we consider in the project, waste is stored in large concrete silos (e.g. 6x6m wide and 16m deep). Some of silos are filled with water to reduce radioactive contamination. In many cases, the silos contain mainly a low-level radioactive waste, which consist of debris from plant reconstruction as pieces of wood, bricks, scaffolding, compressible artefacts like protective gloves, shoe covers and clothing, and other non-compressible material such as tools. Decommissioning of such facilities is performed by building large complex robotic cells above the silos. The cell provides access to the silo content where the waste may be retrieved through a small opening. The cells are designed to enable possible radioactivity from the waste and fully contain the radioactivity of the waste during its processing.

The of-the-shelf robotic equipment can bear about ten times higher radiation dose than humans. The weakest robotic component is electronics from the radioactivity point of view. Electronics can be replaced.

The use-case considered in RadioRoSo relates to the above mentioned silos and concerns decommissioning of reactor fuel rods debris coming from Magnox type reactors used in UK, Italy, Japan in 1950-1970s. The name comes from the magnesium-aluminium alloy used to clad the fuel elements inside the reactor. The usual Magnox fuel element had about 6cm in diameter and about 1m in length. The actual fuel element consists of a few tens of metallic uranium pellets, i.e. small low cylinders put one on top of the other. This series of pellets kept in place by putting two steel springs on both sides of the rod. The fuel rod outer surface (cladding) is a long cylinder made of magnesium-aluminium alloy (Magnox). Its main function is to keep the plant systems free from radiation contamination. The fuel rod is shown in Figure 1. Our use-case considers smashed fuel rods in debris. This material is called Magnox swarf. The most radioactive elements in Magnox swarf are steel springs to be stored apart from the rest of the debris. Our experiment has to detect springs among other debris and pick them up. When the springs are isolated from swarf, the resulting material is classified as low level waste. The steel springs contain a radioactive isotope cobalt 60. Removed springs are put in special led pots, which are subsequently packaged into larger containers. The procedure is performed by remotely operated manipulators these days. However since this is rather delicate tasks (the springs are only a few centimetres long), it results in a very slow process. It is estimated that only 300 kilograms of waste are processed per day, which means that with this rate the processing of Magnox swarf in one considered site will require 6-7 years.

Imagine a custom manipulator and gripper, remotely human operated, is submerged from the bottom of the cell into the waste from the opening at the top of the silo. A batch of waste is pulled-up and moved to stainless steel trays in the cell. Material that does not fit in the tray (e.g. pieces of scaffolding) are removed also using master-slave manipulators and placed in special machines to be cut in pieces or folded. The tray with the debris is sorted out by another robot. If it is performed by humans, the manual operation is unacceptably time consuming. The reported use-case prepares robot, sensors, perception and manipulation skills, which should work almost autonomously and replace the human labour.

2. Task formulation

The reported task aims at demonstrating that automation of the described use-case may be achieved by autonomous robotics faster than current remote operation by humans. It should reduce the operational costs, possibly also the installation cost, and occupational radiation doses of the operators. RadioRoSo experiment aims at validating this claim by mimicking real conditions in a laboratory environment. The demonstrated system should be cost efficient with respect to the current manual sorting. The hardware employed should be able to operate in medium level radioactivity environment, typically in the range of tens μSv/h to units of mSv/h or it should have and radioactivity resistant equivalent.

The task concentrates to Magnox swarf sorting. The shape and material of target objects (springs) are already known and thus the problem is their detection in a cluttered environment. The main challenge in this case is to obtain high accuracy in spring localization so that a precise grasp can be achieved and false positives avoided.

Figure 1. Magnox fuel rod .(length: 1m, weight: 10-12kg)

3. Related work

In the context of nuclear waste sorting applications, we are only aware of a single research project recently funded by the European Commision: RoMaNs (Robotic Manipulation for Nuclear Sort and Segregation) [3]. The objectives of RoMaNs are wider than RadioRoSo in terms of research. The novelties of RadioRoSo are a) the use of dual-arm robot to deal with complex materials, b) ability to manipulate soft material commonly encountered in low-activity waste such as uniforms, gloves, wires etc. c) demonstration of complete autonomy on the task of Magnox swarf sorting.

From a technical point of view the problem may be characterized as a vision-based grasp planning problem which is a well-researched subject [4]. Since for the particular task the shape and material of target objects (nemonic springs) are already known the problem may be addressed using 3D object localization techniques. Both template-based [6] and sliding-window based [7] techniques are relevant to this end. Pick-n-place operations under clutter were also considered in the recent Amazon picking challenge [8].

4. Proposed system architecture

The proposed system architecture is shown in Figure 2. The system consists of the following functional components.

A. *Loading*
   A batch of Magnox swarf waste (the current size of the batch is 30 kg) is placed inside a tray of dimensions 1.2m x 0.80m x 0.15m, size of the Europallet. For this size of tray the height of the heap is approximately 5cm. The process is effected by means of a manipulator or conveyor belt mechanism. The process will be simulated in laboratory conditions by manually pouring the material inside a tray.

B. *De-cluttering*
   A de-cluttering mechanism is applied to the tray to spread the items uniformly and possibly reduce their density. This may be easily achieved by a vibration mechanism and/or by shuffling the heap by means of a mechanical tool and/or by further subdividing the batch in smaller ones by mechanical means. There are commercial solutions for this purpose and thus the experiment will simulate it by means of manually

shaking of the tray.

C. *Radioactivity Source localization*

A radiation detector is applied over the tray to locate possible sources of high radioactive doses. A radiation detector is a device used to detect, and/or identify, radiation emitted from radioactive materials, including alpha particles, beta particles, and gamma rays. Since the springs are significantly more active (contain Co-60) than the rest of the swarf and the environment, the detection of their presence in the tray is expected to be straightforward by simple signal detection mechanisms and existing commercial sensors.

A more challenging is tasks is localizing the springs. Existing solutions, e.g. sophisticated gamma cameras are very expensive (~1M €). A single detector is unable to estimate the location of radiation source or direction of the radiation ray. There are two main solutions to this problem:

(a) Slide the detector over the tray mechanically to improve the sensor spatial specificity. Sliding has to be close to the surface or a special orifice should be used at the detector end-point.

(b) Place several sensors above and/or below the tray. In both cases, multi-source signal detection techniques may be used to recover the location of the source.

The approach (a) is potentially slow (several minutes) since there should be also a "dead-time", i.e. interval required for the radiation to build-up in the sensor for each location. The approach (b) is more promising in terms of costs and measuring time but also more complex to maintain, e.g. due to the radiation sensitivity of electronics. In the worst case, a simple detector can do the job of deciding whether the tray has been cleared from all radioactivity sources. Cheap sensors such as polystyrene based scintillator detector may be used. The combination of both methods also comes into consideration. Nevertheless since localization of sources would have the benefit of shortening the processing time of the following steps, it will be examined at a theoretical level by SURO, which is an expert in the field, and a cost benefit analysis will be conducted. A practical experimentation of the radiation source detection problem would be out of the scope of the project and also very difficult to simulate realistically. Yet the effect of radioactivity based spring localization accuracy will be examined.

D. *Vision System.*

The HW capturing in the visible light spectrum the image of the swarf de-cluttered into an almost single layer will observe the operating field of the robot. Appropriate off-the-shelf camera will be selected. Specifications and placement of the camera will be optimized for the task. Optical sensor electronics are sensitive to radiation so their placement should be in a contained environment (e.g. behind a led glass) or the camera may be easily and rapidly replaced (a short radiation exposure of maintenance personnel may be tolerated). Appropriate illumination sources will be placed in the experimental cell to aid the vision tasks. Standard software and methodology for calibration of the sensors will be used.

E. *Visual "hot-spot" localization.*

This software component consists of vision-based detection and pose estimation (i.e. position and orientation estimation) of "hot-spots", i.e. springs. The 3D shape and material of the springs is known in advance. The input will be images captured by the visible light camera. Several potential objects are identified and their 3D position determined. The positions are then provided to the manipulation and planning component.

F. *Manipulation and Planning.*

The component controls the motion of the manipulator. Standard randomized collision aware planning (e.g. using ROS Move-It) will be performed to identify a set of collision free trajectories that can move the tip of the gripper attached to the arm into spring locations computed by the vision system. The trajectory length and grasp stability measure will be used to select the best motion. The motion plan will be forwarded to the robot controller for execution. A second motion planned is computed so that the manipulator moves the gripper above a led pot. The gripper opens to let the spring fall in the pot.

G. *Grasping.*

A robotic manipulator with an attached gripper is employed. The gripper is designed for stable grasping of the objects of interest and appropriate for low maintenance operation in a radioactive environment. The gripper closes the fingers to grasp the spring. Sensing is employed to recognize a successful grasp. A new gripper will be designed during the project to be used under the constraints of the radioactive environment. The gripper will be actuated with an hydraulic principle using pistons thus allowing placement of the electronics far from the gripper in a protective enclosure. The gripper will have three fingers designed to grasp both springs and larger objects. Fingers are designed to be easily interchangeable to allow for rapid maintenance.

H. *Task Planner.*
This is a software component that orchestrates the task execution and allows for recovering from failures. For example, if a slippage is detected by the gripper, visual localization and grasping stages are repeated. The Magnox swarf is checked for radioactivity after removing all visible springs to ensure no springs are left. In the presence of radioactivity, the sorting process is repeated.

I. *Manipulator.*
Off-the-shelf industrial manipulators are normally not suitable for operation in the radioactive environment. Custom manipulators are usually built by contractors such as NES or robotic manufacturers. In terms of kinematics the above manipulators do not differ from typical off-the-shelf multi-DoF robots and thus a common industrial robot is valid for the sake of the experiment.

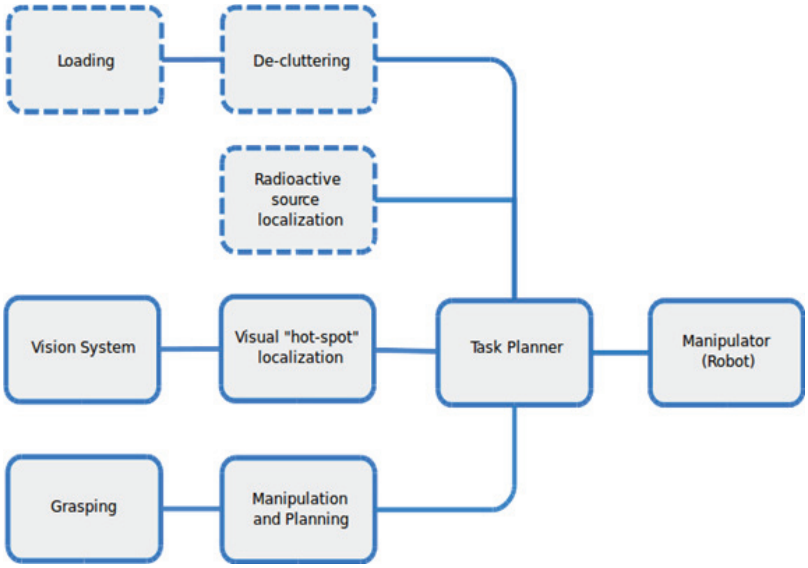

Figure 2. System architecture.

5. Experimental testbed

The experimental testbed is based on the CloPeMa dual-arm robot [5]. It consists of two independent industrial 6-DoF manipulators (Motoman MA1400) placed on a rotating base. Two almost identical copies of the robot exists at both CTU (Prague) and CERTH (Thessaloniki). The CTU robot is also equipped with force-torque sensors. Only one arm will be used for this experiment. The robots are controlled through the ROS operating system. Drivers for all hardware and basic software for collision-aware motion planning, calibration and control are already available. Off-the-shelf visual sensors (2D cameras, 3D sensors etc.) available at site will be used. The placement of the sensors will be optimized for the task. The camera-robot system will be properly calibrated.

Currently the robots are equipped with CloPeMa grippers, pinch-like two finger grippers with compliance support. During the first phase of the project these grippers will be used with a slight modification of the fingertips, see Figure 4, to allow stable grasping of the springs. Phases 2 and 3 will be performed using the custom gripper to be developed by the University of Genova. Appropriate drivers will be developed for this gripper. Through a hardware abstraction layer the experiment could in principle be replicated on other robots that support ROS. The current placement of the manipulators was selected for grasping using a side grasp (i.e. sliding the bottom finger on the table). This has the effect of relatively limited working space in our case where top grasps are preferred without however altering the validity of the experiment.

Mock-up (i.e. non-radioactive) Magnox swarf will be provided by the industrial partner Ansaldo NES to academic partners. The material will be positioned inside a 1.2 x 0.8m stainless steel tray placed on a table in-front of the robot. Mock-up pots will be also provided or fabricated to simulate the actual led storage pots. The pots will be placed on another table close to the robot. Environmental conditions such as illumination will be modeled in experimental setup to be well defined and thus easily replicated in the conditions of the real robotic sorter

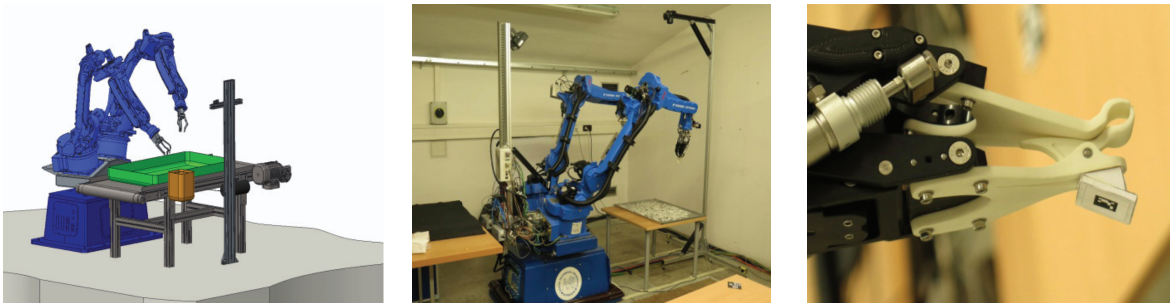

Figure 3: Illustration of RadioRoSo testbed, with CloPeMa robot, vibrating table with a tray, a sensor holder, and a lead pot. Left model. Middle laboratory mock-up. Notice the tray with a mimicked smashed Magnox fuel rod cladding On the right modified fingertips on a gripper.

6. Experimental methodology

The experiment simulates the conditions of the scenario and assesses the performance under various factors. By factors we mean controlled independent variables. There are two factors that may affect the overall performance of the sorting process:

A. availability and accuracy of radiation-based localization;

B. the degree of cluttering that is how the swarf will be single layered, how well the springs will be spatially separated from the swarf and thus visible by the visible light camera.

The first factor has to do with the accuracy of the vision-based spring detector. Obviously the accuracy is expected to be higher if the approximate location of the “hot-spot” is known by means of radioactivity based source localization. Also false positives may be reduced. False positives are costly because the grasping will be performed with erroneous information and in the worst case the gripper will put a wrong piece in the pot. Since we cannot afford simulation of the radiation detector as explained above, this will be simulated by placing the spring(s) in a designated area of the tray. The area of this region will be used as a measure of radiation-based localization uncertainty. The worst case will be that no localization is available and the algorithms are applied on the whole tray image.

The second factor, i.e. cluttering affects both “hot-spot” detection and grasping. In a cluttered case, “hot-spots” are likely to be partly occluded making their detection challenging and the pose computation highly uncertain. Grasping will be also difficult since stable collision free grasps will be hard to find and due to localization uncertainty they are likely to fail. On one hand, one may argue that by reducing the amount of artefacts in each batch, an uncluttered situation may be achieved, which has effective solutions in robotics (e.g. classical pick-n-place). On the other hand, one must not forget that in each batch there may be very few or none of the “hot-spots”. Thus by reducing the size of the batch, the throughput of the system will be negatively affected too. On the other hand, one must not forget that by reducing the size of the batch the throughput of the system will be negatively affected. However de-cluttering of small batch will be fast, capturing the image and its processing takes almost no time, and number of grasps is anyway given by number of springs, that is independent of the size of the batch. Still by varying the batch size in the experiment, we can identify an optimal batch size to maximize cost-effectiveness of the process.

The experiment will repeat the process (detection, picking and placing in the pot) many times. The independent factors above will be altered at each run. Before each run, the de-cluttering process above will be simulated by manually shuffling the artifacts to achieve approximately uniform placement in the tray. A single spring will be placed in the designated area to simulate approximate radioactivity based localization. The following metrics will be used:

A. *The throughput of the spring free swarf through the system (in kg/s).* This cannot be measured in our experiment as it contains manipulation of 30 kg batch of the material to the tray (which is external time for our system, but it is known beforehand) and time to determine whether the 30 kg batch is spring-free by single pixel radioactivity detector (this can be determined by theoretical calculation).

B. The throughput of the swarf containing springs through the system (in kg/s). This is the time needed to process one kilogram of the swarf including putting the certain part of the batch into the robot operating area, de-cluttering, image capturing, and image processing. It can be calculated from time recorded when no spring is included in de-cluttered batch. This time excludes the spring picking time.

C. *Average single item picking time.* The processing time will be computed as above for all runs that result successfully. An approximation of the time required for the previous steps (de-cluttering, measurement etc.) will be excluded.

D. *Vision-based detection precision.* The number of corrects detections divided by the number of all objects in all attempts.

E. *Vision-based detection recall.* The number of correct detections divided by the number of all detections.

F. *Vision-based pose estimation accuracy.* The centroid position error and angular error between computer vision measured position and manually determined position in the image is recorded. The obtained distribution is then characterized by standard deviation and other statistical descriptors.

G. *Grasp error.* Percentage of failed grasping of correctly identified springs versus pose estimation error (i.e. pose uncertainty).

H. *Cost benefit analysis.* A systematic cost analysis of the proposed system will be performed for the various independent factors that affect performance. An operating point that provide the best compromise between quantitative indicators above and overall operational cost will thus be defined. The costs will be compared with the current cost of the procedure as performed by the human operators under similar standards of human performance (e.g. error rate).

7. Conclusions

The contribution described the architecture and methodology of an experiment in progress that will demonstrate the feasibility and cost-benefit of automation of a nuclear waste sorting task. The experiment is driven by the requirements of industrial scenario and will follow strict evaluation metrics to validate overall system performance. Currently the experiment is during the first phase. The final demonstration will be performed in January 2018.

Acknowledgments

Project RadioRoSo has received funding from the European Union Seventh Framework Programme for research, technological development and demonstration under grant agreement no 601116, ECHORD++ (The European coordination hub for open robotics development). The CTU Prague team was also supported by TACR grant TE01020197 Center for Applied Cybernetics.

References

[1] RadioRoSo: Radioactive Waste Robotic Sorter, Echord++ Experiment, http://radioroso.ciirc.cvut.cz/
[2] Echord++: The European Coordination Hub for Open Robotics Development, http://echord.eu
[3] RoMaNS, Robotic Manipulation for Nuclear Sort and Segregation, EU H2020 project, http://www.h2020romans.eu/
[4] A. Sahbani, S. El-Khoury, P. Bidaud, An overview of 3D object grasp synthesis algorithms, Robotics and Autonomous Systems, Volume 60, Issue 3, March 2012, Pages 326-336
[5] CloPeMa: Clothe Perception and Manipulation, EU FP7 project, http://www.clopema.eu
[6] Stefan Hinterstoisser, Vincent Lepetit, Slobodan Ilic, Pascal Fua, and Nassir Navab. Dominant orientation templates for real-time detection of texture-less objects. In CVPR, volume 10, pages 2257–2264, 2010.
[7] Juergen Gall, Nima Razavi, and Luc Van Gool. An introduction to random forests for multi-class object detection. In Outdoor and Large-Scale Real-World Scene Analysis, pages 243–263. Springer, 2012.
[8] Colin Rennie, Rahul Shome, Kostas E Bekris, and Alberto F De Souza. A dataset for improved rgbd-based object detection and pose estimation for warehouse pick-and-place. IEEE Robotics and Automation Letters, 1(2):1179–1185, 2016.