The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Ceiling beam screw removal using a robotic manipulator

Geoffrey Biggs and Tetsuo Kotoku and Tamio Tanikawa
Intelligent Systems Research Institute
National Institute of Advanced Industrial Science and Technology (AIST)
AIST Tsukuba Central 2, Tsukuba, Ibaraki 305-8568, Japan
{geoffrey.biggs, t.kotoku}@aist.go.jp

Abstract—**Within the larger task of renovating an office building, there are many repetitive tasks that are suitable for automation. With the decreasing availability of skilled labour and increasing emphasis on reuse of materials, there is an opportunity to introduce robots that can replace labour for the simpler tasks. This paper describes a robot to perform the task of removing tile screws from suspended ceiling beams. The robot uses a specially-designed tool mounted at the end of an arm. This tool removes screws by turning them between two rollers. The tool is moved down the beam in a single motion, allowing it to remove many screws fast with little operator interaction. RT-Middleware is used as the implementation architecture, which facilitated development by simplifying testing of individual components.**

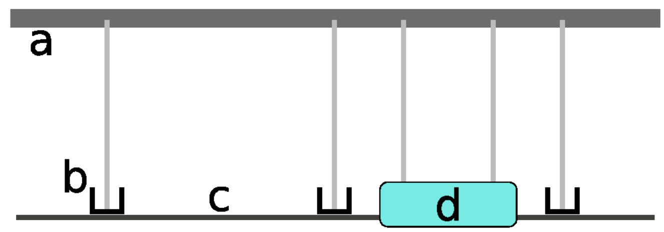

Fig. 1: A common suspended ceiling structure. (a) Building structure. (b) Suspended ceiling beam. (c) Ceiling panels, attached to beams with screws. (d) Light fitting, suspended directly from the building structure.

I. Introduction

Japan, like most industrialised countries, is facing the growing problem of an aging population. A consequence of the climbing average age is a decline in the available workforce, and in particular the availability of skilled workers. The lost labour must be replaced and the efficiency of the remaining labour must be increased. Robots are a natural source of potential replacement labour.

At the same time, the rising cost of raw materials and an increasing awareness of the environmental impacts of human activities has created an increasing focus on recycling materials wherever possible. For example, rather than demolishing buildings and rebuilding them anew, renovating the building by removing and replacing the interior is a preferable option. Ideally, as much of the interior building materials as possible would be reused during this process. This complicates the process of removing these materials, as care must be taken to leave them in a reusable condition. The renovation process therefore requires more time and effort, in a time when it is preferable to reduce the time and effort required to perform such tasks, due to the shrinking skilled labour pool.

This shrinking labour pool makes it necessary to both increase the efficiency of available skilled labour, in order to offset its reduced availability, and make unskilled labourers more efficient and capable. Robots are a possible method for achieving this. Suitably-designed robot assistants can replace some of the lost labour, allowing the remaining labour to focus on those tasks in the demolition and renovation process that robots cannot yet perform, reducing the necessary overall labour and time to renovate the interior of a building.

There are many tasks in the process of demolishing a building where robots can assist the task or perform the entire task, including the removal of ceiling-mounted equipment such as air conditioning units and lights, and removing ceiling and wall panels. This paper describes a robot to perform one such task, removing the screws used to hold ceiling panels to the suspended ceiling beams after the panels have been removed.

This paper begins by describing the problem to be solved in detail in Section II. It then describes the end effector tool designed to aid the task in Section III, followed by a description of the robot hardware, sensing, motion control and the software implementation in Sections IV-VII. Results are given in Section VIII, followed by conclusions.

II. Problem description

A common office building interior uses a suspended ceiling to provide both a pleasant interior and space for building equipment and wiring (see Figure 1). Equipment such as lights and air conditioning vents are mounted on the suspended beams of the ceiling or suspended directly from the building structure. Ceiling panels, typically plaster board overlaid with tiles, are attached to the bottom of the suspended beams using self-tapping screws to provide the finished ceiling surface.

Equipment in the ceiling, such as light fittings and air conditioning vents, are removed first during the demolition process. Following this, the ceiling tiles are cut and removed from the beams, which are then removed themselves.

However, renovating a building's interior does not require removing the suspended ceiling beams. These beams can be reused, often in-place, for the new interior. New ceiling panels can be attached to the same beams with self-tapping screws. Before this can be done, the screws used to hold the old ceiling panels to the beams must be removed. Removing each individual screw by hand is a long and physically demanding task due to the position of the screws above a worker's head. It is, however, a relatively simple and repetitive task and so is ideal for automation.

The problem, then, is to remove the screws from the ceiling beams. To reduce waste, both the screws and the beams should remain undamaged and usable at the end of the screw removal process. Miminal operator intervention and time should be required.

III. Screw removal tool

A. Design requirements

The first part of the problem to be solved is the method of removing the screws from the beams. The need to keep both the beams and the screws in a usable condition limits the removal methods. Aside from the obvious method of unscrewing the screws, other options are cutting the screws off and pulling the screws out.

Cutting the screws off is not feasible primarily because this renders the screws unusable. While the screws have a significant length protruding from the beam below the screw head once the panels have been removed (approximately 12mm), the self-tapping screws used feature a pointed tip that drills a hole for the screw in both the ceiling panel and the beam as it is screwed in. This tip must remain for the screw to be reusable when the next set of ceiling panels are installed. Additionally, if the screw is cut off level with the beam, this would leave the remainder in or on top of the hollow beams, where they could be difficult to remove with the robot.

Pulling the screws out is not feasible because it can damage the beam and may damage the thread on the screw. The force required to pull the screw out of the beam will, at the least, leave a large raised rim around the screw hole. This would make installation of the new ceiling panels more difficult and uneven. It is also possible that the force of pulling the screw out could bend the beam itself, rendering it unusable.

The only option left, then, is to unscrew the screws. While a screw driver tool could be used to remove the screws, this method would be slow. The tool tip would need to be aligned with each individual screw, inserted into the head, unscrew it while lowering it out of the screw hole, and then the screw removed from the tool before locating and moving to the next screw. A faster method of removing the screws is preferable.

All that is required to unscrew the screws is that they are turned. An alternative method of turning the screws to using a screw driver is to place the screw between two rollers, which grip and turn it. As the screw turns, the thread will naturally move through the tapped thread in the screw hole and move the screw out of the hole, with the screw falling out when the tapered tip becomes narrower than the hole.

A tool using rollers can be moved onto each screw from a horizontal direction. Once a screw has been removed, it can be moved up to the next screw and remove that in one continuous motion.

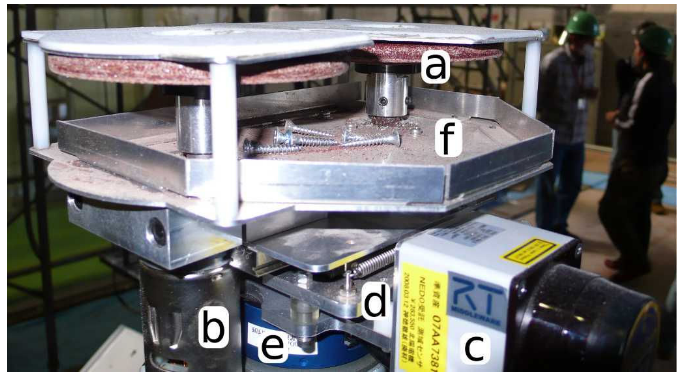

Fig. 2: The tool used to remove screws. (a) Rollers. (b) Roller motor. (c) Laser scanner for beam detection. (d) Horizontal compliance mechanism. (e) Force-moment sensor. (f) Screw collection tray.

B. Tool design

The tool, as designed for this robot, is shown in Figure 2. Two rollers, spaced a short distance apart, are driven anti-clockwise (when viewed from the top) by separate motors. The original iteration of the tool used rubber rollers, but these did not produce enough friction for the screw to be gripped strongly enough to transfer the torque from the rollers and unscrew the screw. The current iteration uses grinder wheels. Testing has found that these produce sufficient friction to grip and turn the screw without damaging it.

Vertical compliance consists of rubber bungs supporting the weight of the tool where it attaches to the robot. These compress under force. The top of the tool is coated with teflon to provide minimal friction with ceiling beams. The horizontal compliance mechanism is a slide-rail mounted between the base of the tool (where it attaches to the robot) and the roller mechanism, and two springs mounted parallel in opposite directions. Each spring pulls the roller mechanism back towards the centre from one side of the tool, respectively. The same mechanism, combined with the round shape of the rollers, also allows for some angular compliance. A tray is mounted below the rollers to catch screws as they fall out of the screw holes. The laser scanner and force-torque sensor are described in Section V.

An important feature of the tool is the provision of mechanical compliance in the axis perpendicular to the direction of motion along the beam. This, combined with the nature of the rollers, removes the need for precise horizontal alignment of the tool with each screw on the beam. As the screws are not precisely aligned down the beam and may be found anywhere in the beam cross-section, and are also difficult to detect with the sensors, such alignment would be difficult, particularly at high movement speeds. With the constructed compliance mechanism, an off-centre screw will strike a roller and force that roller, and thus the tool, to one side, allowing the screw to enter the gap between the rollers. As a screw enters the gap between the rollers, they grip and turn the screw, allowing it to naturally unscrew from the screw hole and fall into the collection tray.

IV. Robot hardware and experimental setup

The robot used for the experiments is shown in Figure 3. The robot itself is a Mitsubishi Heavy Industries, Ltd. PA-10 arm with seven degrees of freedom. The screw removal tool is mounted at its end effector. While such a heavy robot is more difficult for the operator to manoeuvre, the current robot is only for prototyping. A robot used in any production system would ideally be lighter.

The robot is mounted on a portable, custom-designed base. The base contains the robot's controller hardware, power supply and an x86 computer running ART-Linux [1], a real-time variant of the Linux kernel. This is in turn mounted on a lifting trolley, which is necessary for the robot to reach the high beams of the suspended ceiling, 2.5 metres above the floor.

Mounted at the robot's end effector are a Nitta IFS-67M25A 25-I40 force-moment sensor, the tool, and a Hokuyo URG-04LX laser scanner. The force-moment sensor is used in keeping the tool pressed against the beam, while the laser scanner is used to locate and align with the beam. See Section V for more details on the use of sensor data.

The experiments were carried out in an accurate recreation of an office building interior assembled by Shimizu Construction Co., Ltd. This recreation featured flourescent light fittings, air conditioning ducts and ceiling panels, all attached to a suspended ceiling. One section of the ceiling was left uncovered by ceiling panels for tests of the screw removal robot prior to the final demonstrations.

A photo of the robot running on a beam that did not have ceiling panels on it is shown in Figure 4. Differences between execution on these beams and those that had held ceiling panels were found during later experimentation, see Section VIII for details.

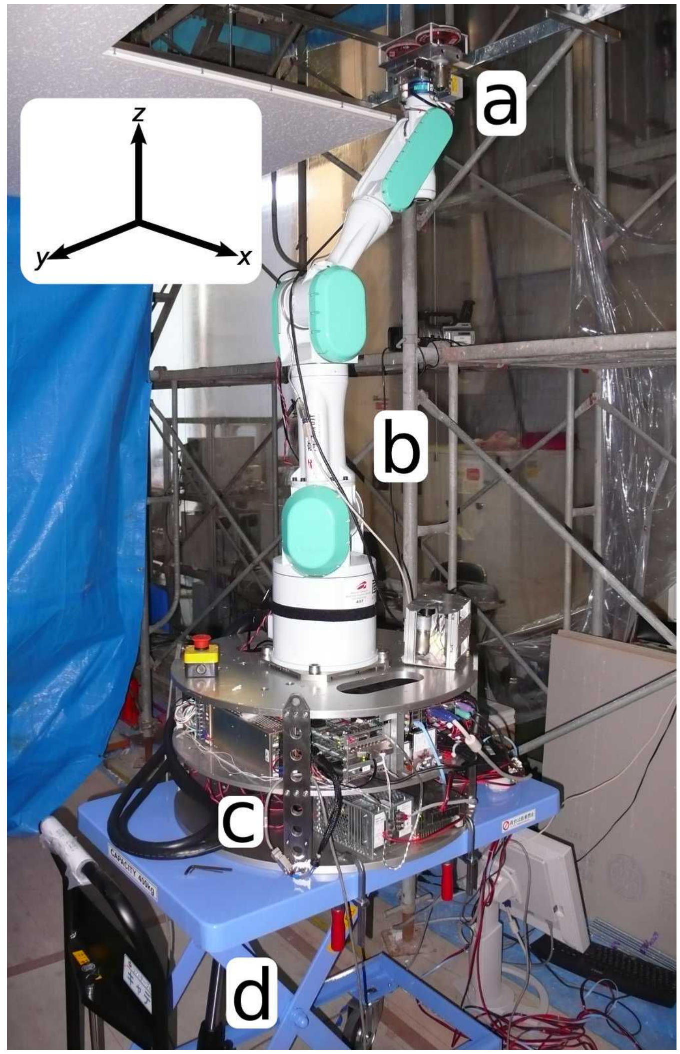

Fig. 3: The robot used for the experiments. Some suspended ceiling panels and beams can be seen at the top of the photo. (a) Tool at the end of the arm. (b) PA-10 7 degree-of-freedom robotic arm. (c) Computer and controllers. (d) Lifting trolley, for reach. The x- and y-axes go into the photo.

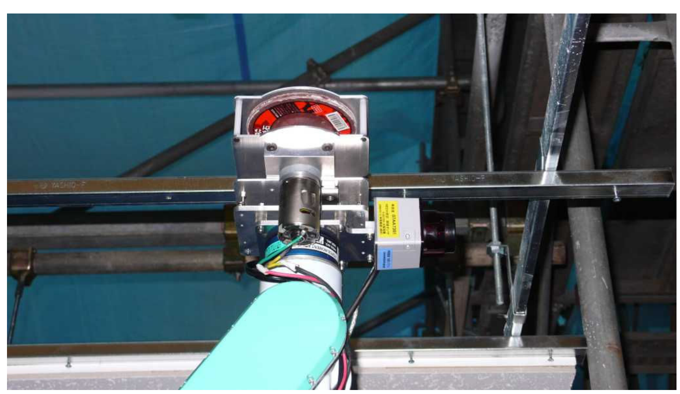

Fig. 4: The tool contacting a suspended ceiling beam, about to remove a screw.

V. Sensing

The robot has two sensors: a force-moment sensor and a planar laser scanner. The force-moment sensor is used to maintain contact with the beam and detect when the tool is in contact with a screw. It provides three force measurements and three torque measurements. These are used by the z- and x-axis controllers directly. Only two axes of the force-moment sensor are used, so a simpler sensor could be used in any final robot design.

The laser scanner is primarily responsible for locating the beam along the y-axis of the tool. Some simple processing of its output is necessary for this. As with all laser scanners, the scan data is somewhat noisy, and in addition to this the beams are a shiny metal, making them difficult for the laser scanner to see. Clustering is performed to remove points that are likely to be noise. The clustering algorithm used is based on Successive Edge Following, a simple difference-based approach [2]. It looks for differences between points greater than a given threshold and breaks the scan data into separate sets at those breaks. A threshold distance for cluster separation of $5mm$ is used. Any clusters with less than three points are removed.

The clusters are then filtered to remove those that are unlikely to be the beam. The centre of mass of each cluster, calculated in robot coordinates, must be within a certain height range. The centre of this height range is the height of the beam, a constant known value. In the implemented robot, an error of $10cm$ is allowed on either side of this height. The width of the cluster along the x-axis of the scan (which corresponds to the y-axis of the tool) must also fall within a given range. This range was set to $2cm \pm 2cm$ ($2cm$ is the width of the beam). Tests found that this filtering accurately located the beam sufficiently often. In particular, when the tool is in contact with the beam or a short distance ($<10cm$ below it), not locating the beam was a rare occurance. Further away from the beam, the noisiness of the scan and the nature of the beam material resulted in regular failures to find the beam, particularly when the sensor was not directly below it.

VI. Motion Control

The design of the screw removal tool dictates the motion that must be followed by the robot's end effector. The need to remove screws quickly also places limitations on this motion. The robot should minimise the time spent aligning with the beam and maximise the time spent removing screws.

Motion control of the robot is divided into two periods of activity: initialisation and screw-removal.

A. Initialisation

Initialisation is the behaviour responsible for initially locating the beam in robot space and aligning the tool with the beam in such a way that it can begin removing screws. The process assumes that a worker has approximately positioned the robot below a ceiling beam, with the tool in a safe rest position well away from the beam. Using an automated initialisation procedure removes the time and ability required for a worker to manually align the tool with the beam.

As shown in Figure 5, the initialisation process begins by calculating the height of the most central cluster detected by the laser scanner, which is assumed to be the beam the robot has been positioned below. This gives the worker a margin of error in their placement of the robot of half the distance between ceiling beams. The height of the beam is easily calculatable based on the calibrated height of the robot's base, the height of the end of the arm above this base from the robot's controller (via forward kinematics), and the calibrated offset of the laser scanner from the end of the arm (the beam's y value can also be calculated based on its position in the laser scan). The beam is continuous along x. Once the beam's height is determined, the tool is moved to a position slightly below the measured beam height. A value of ten centimetres below the beam was used in experiments. This provides for more accurate measurements of the beam's position by making it a larger target for the laser scanner.

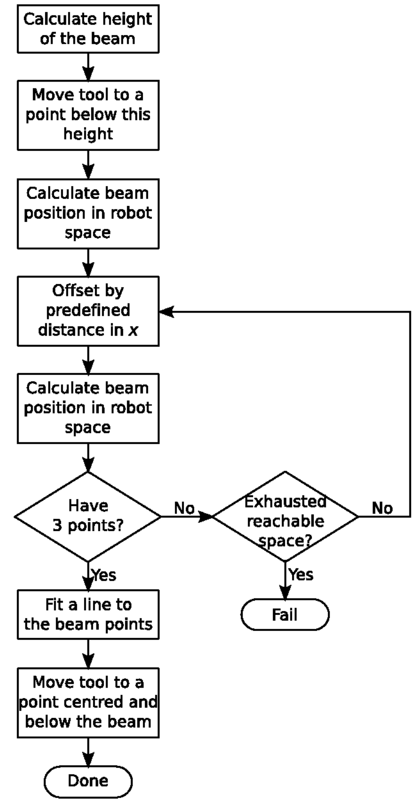

Fig. 5: The process of initialisation is relatively simple.

The process from this point is to locate the beam in robot space at several points along the end effector's x-axis, beginning at the current point and offsetting by 5cm each time. Once three such points have been calculated, a line is fitted to them using least-squares line fitting [3]. This is the line of the beam. If insufficient points are found when the robot has exhausted its reach along the x-axis, initialisation fails.

The reason for finding multiple points and fitting a line is that the laser scanner can only find the beam in a two-dimensional cross section in a plane parallel to the z-axis, which prevents the angle of the beam from being calculated from a single point. Three points are used to give a sufficiently accurate fitted line, given inaccuracies in the laser scan.

Once the beam's line is known, the tool is moved to a calculated point at a pre-defined distance below the beam (on the z-axis), a pre-defined distance back on the x-axis, centred on the y-axis, and with the tool's x-axis aligned with the beam line. The behaviour signals its completion and the screw removal behaviour begins execution.

B. Screw removal

The tool's design requires that it is moved on to each screw horizontally, such that the rollers contact the screw with sufficient force to apply enough torque to remove the screw from its hole. Tests showed that the screws fall out naturally once unscrewed, so no downward force is necessary. The motion control for removing screws can therefore be

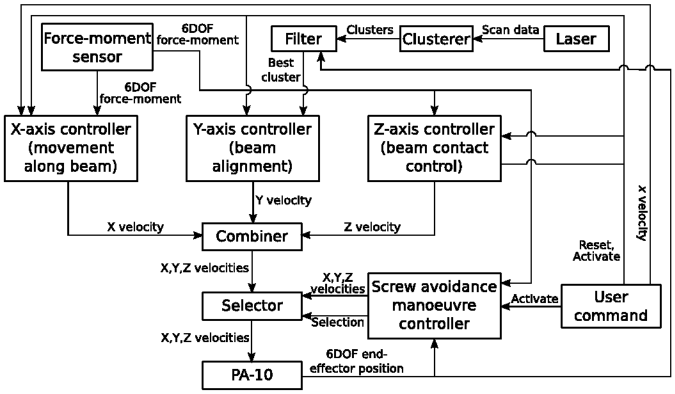

Fig. 6: The movement of data and command signals between controllers and hardware during the screw removal period of motion control.

reduced to a variation of line-following, with the variation being the need to keep the tool pressed against the beam. Due to the initial alignment and compliance of the end-effector, it is not necessary to provide angular tracking of the beam at this stage.

Independent parallel velocity controllers are used for each axis, as described below. The flow of information between hardware and controllers during the process of removing screws is illustrated in Figure 6.

1) x-axis: The desired velocity along the x-axis is controlled by the operator through a simple user interface. This value is damped based on the output of the force-moment sensor to compensate for the time required to remove a screw and prevent screws from being bent by the tool, as would happen if the tool continued moving at the same speed while unscrewing. The default movement speed for the experiments was set to $40mm/s$.

The controller uses a linear proportional drop based on a maximum x-axis force. This maximum was set to 10N for the experiments. When the measured force exceeds the maximum force, the output x-axis velocity is set to zero.

Originally, this damping was applied in both directions (to prevent damaging screws while moving back along the beam – the tool is not double-ended). However, testing found that when the tool encountered a screw it could not remove, it would sometimes get the screw slightly jammed between the rollers. Moving back off the screw slowly easily corrects this jam, but during this movement some force is generated that would cause this backing-off manoeuvre to be damped to the point of being cancelled out. To account for this, damping is now only applied in the direction of movement along the beam. As backward movement will only occur at the request of the operator, this is deemed sufficient.

2) y-axis: The y-axis controller is responsible for keeping the tool centred on the beam as it travels down it. This is accomplished with a PI controller. The y offset of the best cluster in each laser scan is calculated, and a moving average of the three most recent values is kept. This value is the input to the PI controller. Because the target of the controller is a y offset of zero, this value is also the error. In the experimental system, the controller's proportional gain was set to 0.5 and its integral gain set to 0.01.

3) z-axis: The task of the z-axis controller is to keep the tool pressed against the beam, but at the same time prevent it from pressing hard enough to limit movement, or bend or otherwise damage the beam. A PI controller is used. The force on the z-axis as measured by the force-moment sensor is used as the input. The difference between this force and a defined target force is used as the error. For the experimental system, the target force was 5N. When the tool is not contacting the beam, the measured force is lower than this value and so the tool will rise to contact it. The controller's proportional gain was set to 0.5 and its integral gain to 0.001.

This controller also detects first contact with the beam and activates the x- and y-axis controllers when this occurs. During the time preceeding first contact, the controller raises the tool at a fixed velocity of $15mm/s$.

C. Skipping screws

It is possible that a screw will not be able to be removed by the tool. This situation is ultimately determined by the operator. The robot will have already reduced its velocity along the beam to zero when it moved up against the screw, preventing damage. While some screws may take some extra time to remove, occasionally a screw may be encountered that simply cannot be removed. It is best to pass by that screw and resume normal behaviour rather than stop operation altogether so the screw can be removed. This will allow a worker to remove these screws manually once the robot has completed its task.

The operator can signal that this situation has occured using the user interface. This will switch from the parallel controllers to a separate behaviour. This behaviour executes a preset sequence of movements that backs the tool away from the screw, lowers it from the beam, and moves it past the screw. The tool is left in a pose similar to the post-initialisation pose. The selector is then switched back to the controller outputs and screw removal resumes.

VII. SOFTWARE IMPLEMENTATION

The robot software has been implemented as RT-Components for the C++ and Python versions of the OpenRTM-aist-0.4.2 architecture [4]. The component layout in OpenRTM-aist's RTCLink tool is shown in Figure 7. The components responsible for interacting with hardware (`Hokuyo_AIST`, `PA10 Interface` and `ftsensor`) were written in C++; the remainder were written in Python using the Python version of OpenRTM-aist. The user interface component uses PyQt [5].

Due to a bug in the architecture that does not correctly duplicate data transmitted over a one-to-many connection, when the inputs of several components are connected to an output of a single component, only one of those components will receive the data. To overcome this, a component that

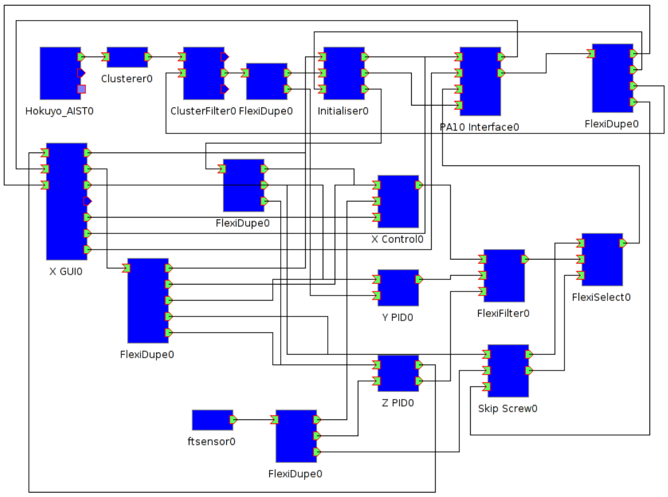

Fig. 7: The various components of the system laid out and connected in RTCLink. There is a rough alignment with the individual behaviours and controllers of the system.

duplicated data was created and only one-to-one connections were used. This introduces a small delay, but it was not found to impact on the system (although it does make the system appear to be more complex than it is).

VIII. Results

The robot was trialed in a test environment. Tests were performed on beams that had screws put into them by construction workers, but which had not been holding ceiling panels. On these beams, the robot successfully removed most of the screws, although some screws could not be removed. In each case, the screw skipping behaviour was invoked and the robot continued successfully. The average time to remove each screw was approximately 6 seconds per screw. With tuning, this time can be reduced.

Figure 8 shows the path taken by the robot along one beam. The jolts in the position of the tool caused by the forces generated while removing screws are clearly visible. The sequence of movements performed at operator request to skip a screw can be seen in the xz plane. Finally, note the short movement from left to right in the xy plane (the initialisation sequence at $y = 0$) followed by aligning with the beam. The figure-8 shape is caused by the robot returning to its start position automatically upon reaching the end of its reachable space.

After the robot reached the end of each beam, it was repositioned approximately under the next beam and the process begun again.

Tests performed on beams that had been holding panels (which had recently been removed) were less successful. The tool was unable to grip and remove any of the screws. Dust left on the screws by the panels is suspected to be the cause, by reducing the friction between the rollers and the screws.

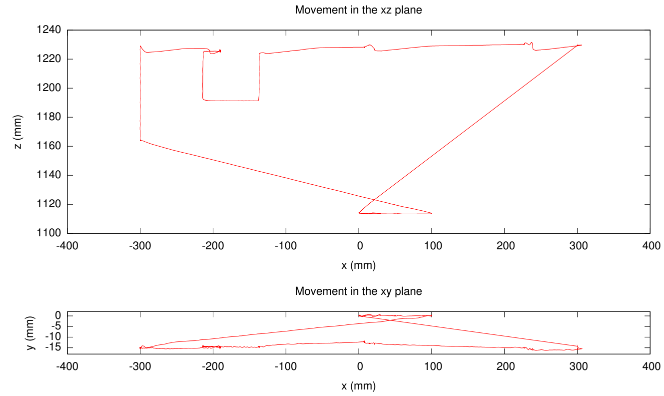

Fig. 8: Tool movement in the xz and xy planes while removing screws from a beam.

Possible solutions to this problem are different rollers or some form of cleaning attachment at the front of the tool.

IX. Conclusions

A robot has been created that can remove screws used to hold ceiling panels to the suspended ceiling beams of office buildings. The robot uses a non-destructive procedure that does not damage the screws or the beams, leaving both in good condition for reuse in building renovations and reducing waste. This robot requires little operator interaction and does not require the operator be skilled. This reduces the labour, number of workers and time required to demolish the interior of a building.

Future improvements include adding a yaw controller that can maintain alignment between the x-axis of the tool and the beam. This will allow the robot to be pushed along a beam by a worker when it reaches the end of its reach along the x-axis without needing to reinitialise the robot.

Acknowledgements

This study was financially supported by NEDO project for Strategic Development of Advanced Robotics Elemental Technologies.

References

[1] (2009) ART-Linux. [Online]. Available: http://www.dh.aist.go.jp/en/research/humanoid/ART-Linux/
[2] A. Siadat, A. Kaske, S. Klausmann, M. Dufaut, and R. Husson, "An optimized segmentation method for a 2D laser-scanner applied to mobile robot navigation," in *Proceedings of the 3rd IFAC Symposium on Intelligent Components and Instruments for Control Applications*, June 1997.
[3] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes: The Art of Scientific Computing*, 3rd ed. New York, NY, USA: Cambridge University Press, 2007, ch. 15.
[4] N. Ando, T. Suehiro, K. Kitagaki, T. Kotoku, and W.-K. Yoon, "RT-middleware: distributed component middleware for RT (robot technology)," in *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*, August 2005, pp. 3933–3938.
[5] (2009) Riverbank : PyQt : Overview. [Online]. Available: http://www.riverbankcomputing.co.uk/pyqt/