Experimental tests of 'Bidi-bot': A mechanism designed for clearing loose debris from the path of mobile search and rescue robots

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Abstract

Urban search and rescue (USAR) robots have the potential of identifying the location of trapped people following a disaster. The majority of survivors in open spaces will be rapidly located and extracted by rescue personnel. Therefore, the greatest challenge for rescue robotics is to penetrate deep within collapsed buildings to search for survivors. In this paper, several robotic challenges are presented to represent- some of the challenges faced within a collapsed building. A robotic mechanism, termed *the sweep-extend mechanism* is proposed as a means for mobile search and rescue robots to clear a path through loose debris. The mechanism has been mounted on a mobile platform and tested against the proposed scenarios. The mechanism was demonstrated to move debris, such as bricks, away from the path of the robot. The work also highlights limitations in the mechanism's ability to deal with densely packed debris, collections of large debris, and the need for robust dust shielding.

Keywords: Urban search and rescue, robot, manipulator, debris, four-bar mechanism.

1. INTRODUCTION

Buildings collapse due to failure of their supporting structure [1]. It is very uncommon for a building to completely collapse. Therefore there are often open spaces within the collapsed structure that can serve as survival zones for people and allow movement from one part of the building to another. Objects within a building contribute to providing additional structural support and help to create voids; for example furniture, door frames and building services such as pipes and wires can all provide resistance to collapse. Voids are structurally unsound and cramped making it extremely hazardous and difficult for rescue services to locate and extract trapped survivors.

Due to the relatively expendable nature of machines compared to human or canine searchers, robotics is becoming an increasingly popular research area in urban search and rescue (USAR). The majority of survivors in open spaces will be rapidly located and extracted by rescue personnel. Therefore, the greatest challenge for rescue robotics is to penetrate deep within collapsed buildings to search for survivors. The movement capability of USAR robots is the dominant issue in USAR robot design [2, 3]. To penetrate deep within the debris pile, robots will need to navigate through or under loose debris; they will no longer have the option of going around or over [4]. Moreover, even in relatively open spaces, debris can become caught on robots and prevent progress [5]. There are two approaches to mobility within debris piles; design of slender, flexible and dexterous robots and/or the use of manipulators to clear a path.

Snake robots have the potential to wriggle through debris and therefore reach difficult to reach areas. Several impressive prototype snake designs have been created [6, 7], however snake robot locomotion is complex to create/control and, using current technology, slow. It is possible to combine the robustness and speed of tracked robots with some of the dexterity of snake robots [8]. Prof Hirose's impressive work [7] implemented multiple track modules combined together by active movement of one module relative to another. However, the combination of these two features results in a system too bulky to wriggle through a densely cluttered environment.

Very few USAR robots have been designed with a manipulator; some of these include Mesa Robotics' Matilda, iRobot's PackBot, Kuchera's teleMax and Foster-Miller's Talon, all of which have general purpose manipulator arms. TerminatorBot [9] has 2 serial-link arms with a shoulder joint, and uses the arms to pull itself during locomotion. Their debris manipulation capabilities have not been thoroughly investigated. The chaotic clutter in a search and rescue environment presents a significant challenge for conventional pick and place robotic technology; a manipulator would have to be operator-controlled or use image processing to pick and place every piece of debris. The time taken for each pick and place operation would preclude deployment of the system.

The approach taken here considers moving through debris as analogous to animals digging. The authors have previously investigated the biological inspiration of digging robotics for one of the most specialised diggers; the European mole [10]. A side-by-side comparison of the mole morphology and the proposed robot design is shown in Figure 1 with a detailed comparison available in [10].

Previous work has analysed a mechanism capable of burring in search and rescue scenarios [11] and presented some challenging scenarios for search and rescue robots [12]. This work details attachment of the mechanism to a mobile base, the mechanism performance in attempting these scenarios and user experiences.

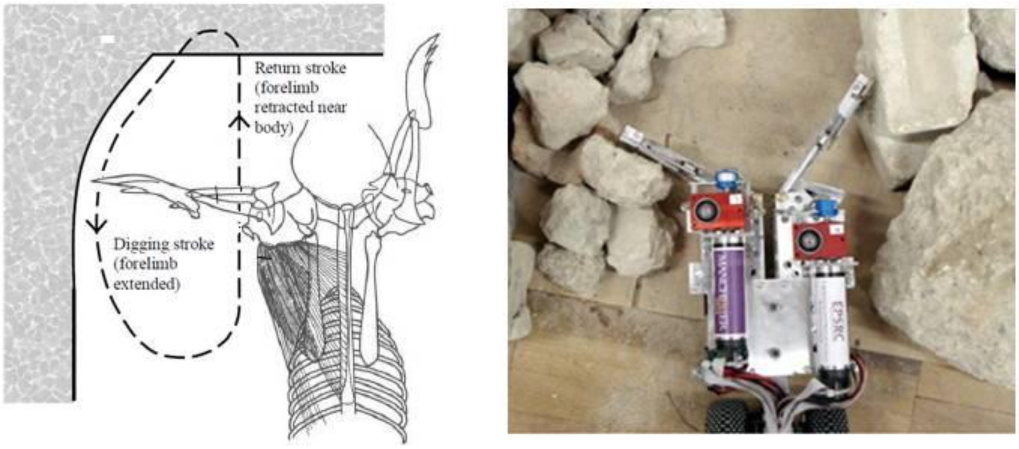

Figure 1: Side-by-side comparison of mole morphology and robot design.

2. EXISTING DEBRIS FIELD KNOWLEDGE

Previous studies have accepted that knowledge of the statistical structure of general collapse debris is important [13, 14] but have not performed work to fully address this. Simulations are used to collapse simulated models and observe the outcome [15]. However, it is almost impossible to capture the chaotic nature of a real building collapse. This section analyses the information available in the literature and is developed from the author's previous analysis of debris fields [12].

Building construction types range from light timber framed buildings which are low rise to structural steel reinforced concrete high rise buildings [16, 17, 18]. The construction of buildings, including the materials used and their overall weight, will greatly affect how the building collapses and hence the types of debris components.

Elements within a debris field will consist of the following [16, 19]: Concrete debris, steel frames, timbers/wood, concrete blocks and masonry, piping/ducting, floor coverings, paper, earth/sand/dust. From a survey of the existing works on USAR research, including robotics related studies, it is possible to gain an overview of debris fields including debris field structure, and the creation of voids.

2.1 Debris Field Structure

In the context of USAR, certain metrics have been identified which form the basis for the current robot manipulator design. Debris fields are generally characterized by a void. The entry size of the void has been reported as being of the order of 0.5m or less [20, 21]. The orientation of the entrance may vary, and lead to an immediate vertical drop. Within the collapse site, space is generally very confined and is characterized by small headroom less than 0.5m [4]. Flat and horizontal surfaces are generally absent as a result of collapse, and the general terrain may consist of small, precarious and uneven surfaces interspaced with vertical rises and drops between 0.3m and 0.6m [4, 22]. Bent metal such as concrete reinforcing bar and piping may be jagged in nature and affect mobility and traction, leading to entanglements. The terrain itself may be dynamic due to the unsound structure, and layers of dust may hide potential hazards. Moveable rubble varying from pebble to tennis ball-sized pieces may be encountered [23].

2.2 Creation of Voids

The constituent components of the debris field can be thought of as fitting into three categories based on the structural hierarchy in a building [16, 17, 19] as shown in Figure 2 (a).

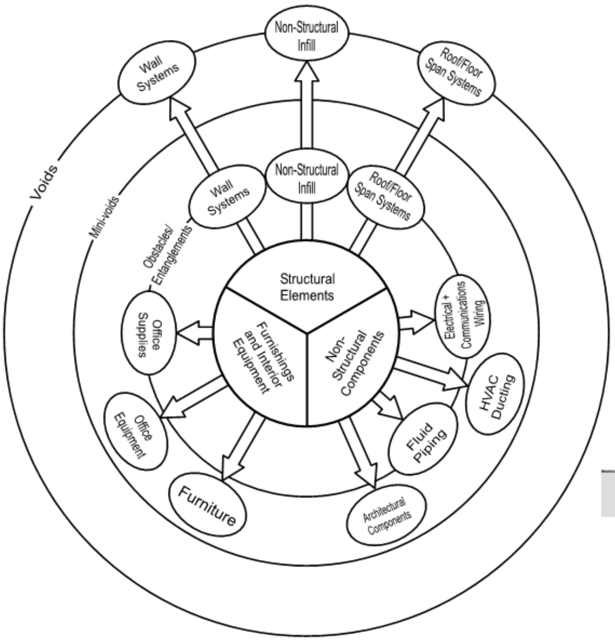

Figure 2 (a): Debris field elements diagram

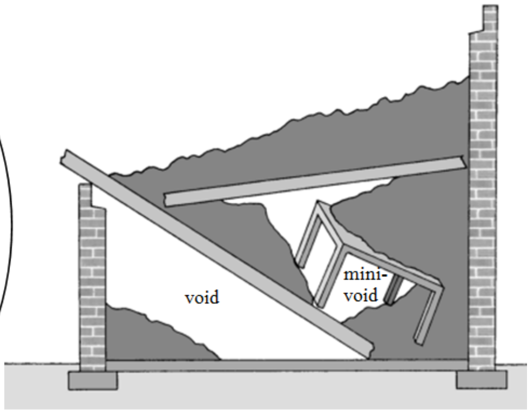

Figure 2 (b): Void and mini-void creation

Voids are created by the structural elements; the largest and strongest components of the building. The secondary category is here defined by the authors to be: Mini-voids - small spaces created by non-structural elements either within voids or under debris piles. These non-structural elements can be larger pieces of office equipment (e.g. photocopiers), furniture items, architectural components (e.g. office partitions, suspended ceilings) or HVAC (Heating, Ventilating, and Air-Conditioning) ducting. Mini-voids will most likely never be larger than a void as they are by definition constructed from material contained within a level of the building (Figure 2 b). Smaller elements within these categories will more likely become obstacles/ entanglements, to block the entrance or exit from voids and generally restrict movement. Structural items such as walls, floor and roof systems may form both voids and debris within voids or mini-voids depending on the resulting destroyed size of these elements subsequent to collapse.

2.3 Robot specification

The information on debris fields allowed the creation of a specification for a robot capable of successful interacting with loose debris in search and rescue scenarios (Table 1). The specification is challenging for a robot designer, in particular there is a trade-off between the robot size and the force produced; larger forces would enable manipulation of larger pieces of debris, but also in practice increase the robot size and hence the forces required to clear a path.

Criteria	Details
Size	As small as possible. Must be smaller than 0.5m width and height to enter voids. Length as short as possible to allow mobility through cluttered environments.
Dexterity	The ability to manipulate objects away from the robots path, including: • Free hanging/loose cables • Randomly distributed debris (not interlocked) varying in size from golf ball (42mm) and smaller, to bricks (approximately 230mm x 110mm x 65mm) and equivalent concrete size pieces. • Small loose pieces of debris (such as sand, dust and mud)
Workspace	The end effector is required to move debris away from the path the robot. If two arms are used, each arm must have a workspace equivalent to half the robot diameter
Actuation	The robot should be actuated thorough electric motors via a remote centre of operation principle to protect the motors from damage when interacting with debris and allow dust shield
Forces	To apply sufficient forces to manipulate loose debris of the scale specified in dexterity characteristics. Experimental tests on bricks with mortar (from a demolition site) found the coefficient of friction between the rough mortar and concrete to be approximately 0.5 and a smooth brick face against concrete to have friction of 0.3. The force required to lift the brick with mortar was approximately 35N. The force required to slide bricks with rough mortar was approximately 18N. Interlocking bricks will require extra forces. Experimental tests revealed that 50N was capable of manipulating bricks when piled up to 3 bricks high and this force was specified as a trade-off between functionality and feasibility.
Control	Simple to control. The robot should require direct user control of a manipulator (i.e. the user should not be required to position an end effector in three dimensional space to move each piece of debris).
Mobility	The device should have the capability of driving over loose debris to gain access to voids that are raised.

Table 1: Robot specification

2.4 Challenging scenarios for robots

Several scenarios are presented in [12] to test robot performance against the specification and as a challenge to USAR robot developers. The scenarios are illustrated in Figure 3. The dimensions are approximate and are made with reference to the approximate expected void space size of 0.5m or less.

A. Raised and Rotated Void with Entanglements

Scenario A contains a passageway blocked by a number of long and slender metal bars that create a lattice with multiple void entrances of various shapes, sizes and orientations. Cables are intertwined in the metal structure presenting possible entanglement hazards. In an alternative situation, square cross-sectioned wood pieces could be encountered, for example in an area of mainly light structural buildings that suffered a tsunami.

B. Raised void with manipulation and mobility challenges

Scenario B models a lean-to collapse partially blocked with brick sized randomly shaped concrete pieces and broken mainly loose light wood. These represent structural elements destroyed during a building collapse which must be traversed over or moved such that a robot can pass through. Some of the wood will be meshed together and will present a challenge in its manipulation.

C. Floor level void blocked with large debris

Scenario C represents a lean-to collapse containing a floor level void almost completely blocked with structural bricks and brick sized pieces of concrete.

A larger amount of debris must be moved in order

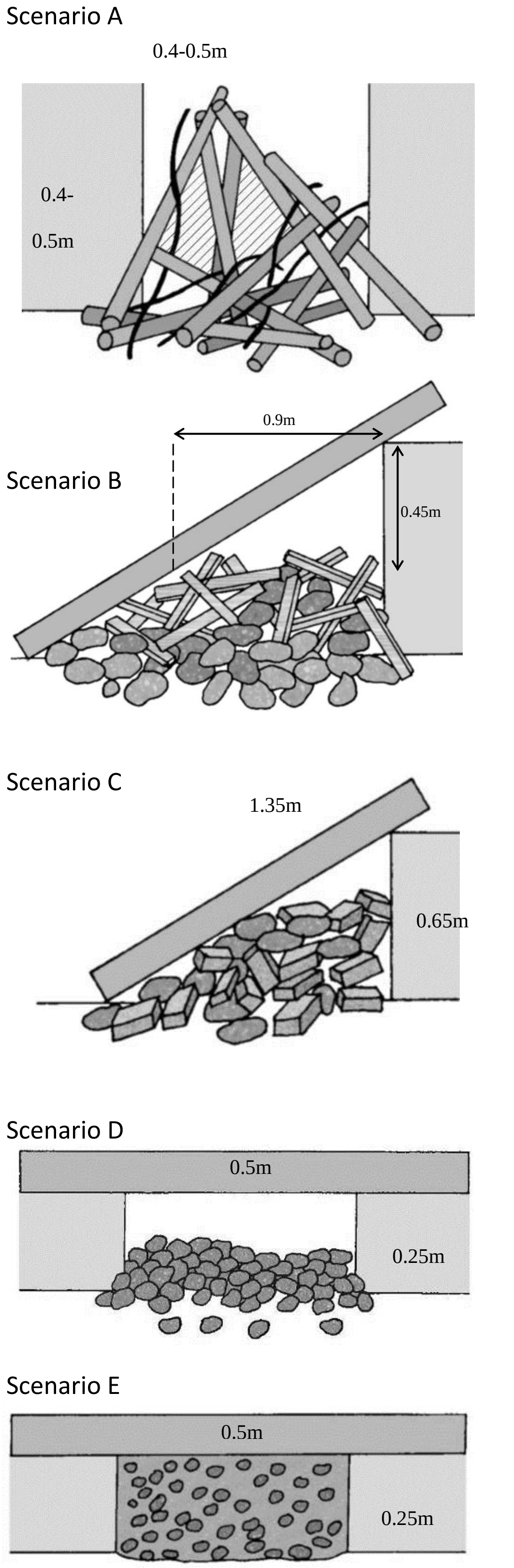

Figure 3: Proposed scenarios to test USAR robots

to pass through compared to the previous scenario and may be manipulated either with a pick and place type technique or by simply pushing the debris.

D. Floor level void blocked with dense small debris

The pancake collapse is typical of collapses in larger, heavier high rise structures and results in greater destruction and smaller resulting pieces of the structure. Scenario D is a parallel pancake collapse containing a floor level void, partially blocked with densely packed ¼ bricks and golf ball sized concrete pieces. It is not possible for a robot to push/plough through the debris due to the density of the material.

E. Floor level completely blocked path

Scenario E represents a densely packed situation due to the forces experienced during collapse. The parallel pancake structure is completely blocked with very fine material such as sand, dust and mud scattered with golf ball and smaller sized concrete debris. Entry would be floor level and would require a digging system to pass through.

3. ROBOT DEVELOPMENT

The need to clear debris from the path of a mobile robot is an issue that has not been addressed in current search and rescue robots. Two options are available with current technology, (i) Use the robot to push (bulldoze) rubble forward in the hope that it can be pushed to one side. (ii) Use conventional pick and place manipulators to individually grasp and maneuver debris away from the robot path. Pushing rubble is not a viable option for most situations as debris will soon pile up to create an impassible obstacle. Conventional pick and place manipulators would have difficulty grasping the varied debris shapes, struggle to exert sufficient force to lift the debris and require close, time consuming operator control. The approach taken here is to use biological inspiration from 'moles' to design a mechanism with inherent properties that enable the clearance of debris. The test scenarios are designed to be an extreme test of robot performance and it is unlikely that any mechanism would be capable of passing them all. A common task for such a system is anticipated to be moving individual pieces of debris from the robot path that otherwise would coalesce and prevent the robot motion.

A new type of end effector system for a mobile robot has been developed based around a mechanical configuration termed here as, *the sweep-extend mechanism*. Figure 4 illustrates the robot concept. Two external manipulators protrude from the robot body to manipulate external debris. The end effectors are required to move small, loose debris from the front of the robot to the side through the use of two independent arms. Therefore, there is a requirement for each arm to move through the motion as illustrated in figure 5. This motion is based around biological inspiration of the European mole as discussed in previous work [10].

The research objective of this work is to create a mechanism that can move an output tip through cyclic motions as indicated in figure 5, whilst satisfying the following criteria: i) the extension/retraction can be altered during the motion ii) the actuators are located away from the mechanical links and output tip to protect them from damage in harsh environments and allow the actuators to remain in a fixed position relative to the body, iii) the actuators continually move in the same direction to minimise backlash effects in the motor and achieve better efficiency (motors are far more efficient running in a single direction within velocity bounds) iv) Force requirement: The mechanism should minimise scaling of the input torque from the motors with respect to the output torque.

There are many mechanisms described in the literature that produce complex movement from continuous rotation: Swing-arm quick return mechanisms that use a constant input rotation to produce a linear motion with different speeds for extension and retraction [24]; geared 5 bar mechanisms that use a combination of multiple links and gears around the crank; and treadle drive mechanisms that are used for moving sewing needles and driving grinding wheels. However, these mechanisms often require sliders or gears close to the output tip which is very undesirable in harsh environments. Moreover, the mechanisms only provide movement in one motion plane whereas the movement trajectory extension/retraction must be adjustable mid-cycle.

Figure 4: Robot concept

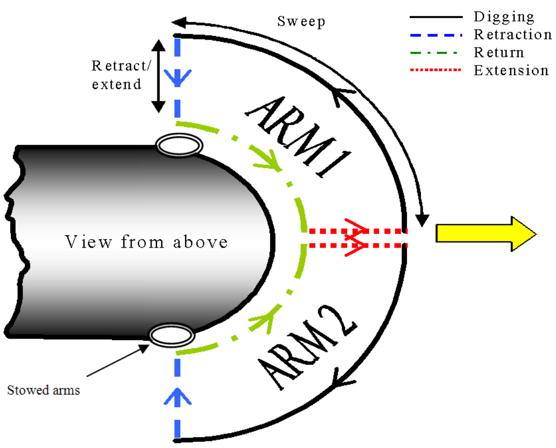

Figure 5: Biologically inspired trajectory

In a robotic context, the use of a conventional two jointed servo controlled robot arm requires the actuators to continually change direction and be exposed to harsh conditions. It is possible to use additional mechanical links to mount the actuators at the base of the joint [25], however the motors are still required to continually change direction which is wasteful of energy and places extra wear on the mechanism.

It is possible to add a servo controlled prismatic joint (linear extending) to the cyclic motion of a conventional mechanism. However prismatic joints provide small amounts of strain (typically around 60%), and are notoriously vulnerable to damage from dust, dirt and side loads. The approach taken here is to combine two four bar mechanisms to create a system that produces the desired cyclic motion and allows for variation of extension and retraction during the cycle.

3.1. Mechanism Design

The full mechanism design and analysis is presented in [11], but briefly presented here for completeness. A combination of two four bar mechanisms is proposed to produce the required output motion. Consider the Grashof crank-rocker four-bar mechanism [24] shown in figure 6. A continuous rotation of link 1 (L_1) around joint J_a (the crank) results in link 2 rocking backwards and forwards around joint J_d (the rocker). θ_1 is the input angle, θ_2 is the rocker angle and θ_3 and θ_4 describe the angle around the mechanism centre line L'. The relative lengths of the links determine the type of four bar mechanism, for a crank-rocker configuration the lengths must meet the following criteria ($L_1 + L_4 < L_2 + L_3$). A second four-bar mechanism is combined with the first to have a coincident joint J_d, but to be rotated from the first four-bar by an angle r_2 (figure 7).

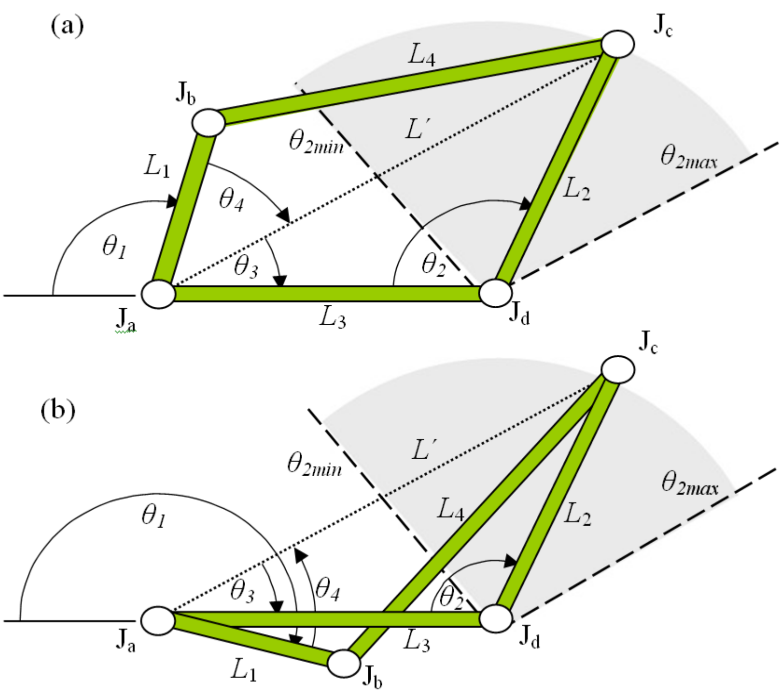

Figure 6: Four-bar mechanism in a) positive and b) negative positions

The subscript (a) is used to identify parameters on the first four-bar linkage and the subscript (b) for the second four-bar linkage. The motors M_a and M_b apply input torque to rotate the joints J_{aa} and J_{ab}

respectively. Joint J_c remains at a distance L_2 from joint J_d but the end of L_2 is now extended to the overall length L_5 on both mechanisms. The output of both four-bar mechanisms are combined through two additional links L_{6a} and L_{6b} connected to joints of links L_{5a}, L_{5b} at J_{ea} , J_{eb}. L_{6a} and L_{6b} are joined at joint J_f. The crank angles (θ_{1a} and θ_{1b}) and rocker angles (θ_{2a} and θ_{2b}) are measured with respect to a line along link L_{3a} and L_{3b} respectively. The whole mechanism is rotated by an angle (r_1) to align its extension with the horizontal plane. The motors rotate in the opposite direction to the measured angle to use positive four-bar link configurations while performing the sweep action (maximum extension). The workspace is defined by a circumferential angle R, inner radius W_i and outer radius W_o.

The size of debris influences the size of the mechanism through the force output and size of individual pieces of debris. The maximum force output was 50N. The reach of the mechanism was designed to manipulate half size UK bricks (115mm x 100mm x 65mm) where the mechanism can reach beyond the centre of mass (57.5mm). In digging applications, R would typically be 90^0 to ensure the debris is moved from the front to the side of the robot. W_i was chosen to be as small as possible whilst being large enough to exceed the robot width determined by the size of actuators and mechanism links. W_o was chosen to be as close to $2W_i$ whilst maintaining the correct movement range.

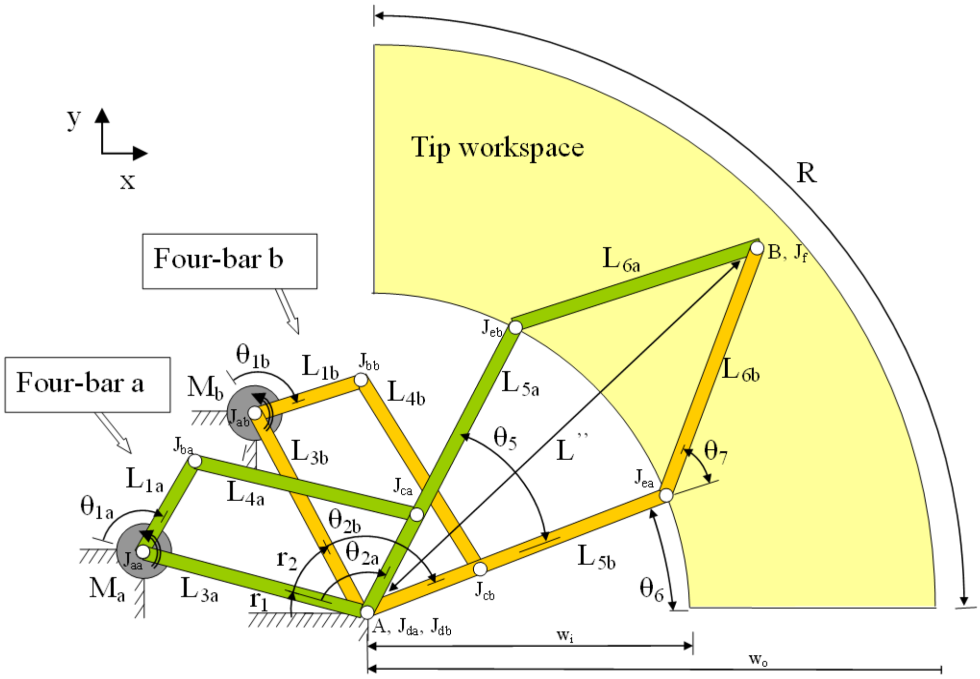

Figure 7: The mechanism configuration and parameters

Figure 8 illustrates the mechanism output at key points. The mechanism is designed, and has been demonstrated, to be capable of altering the reach and extend range during motion [11]. Here only trajectories of the full workspace will be presented.

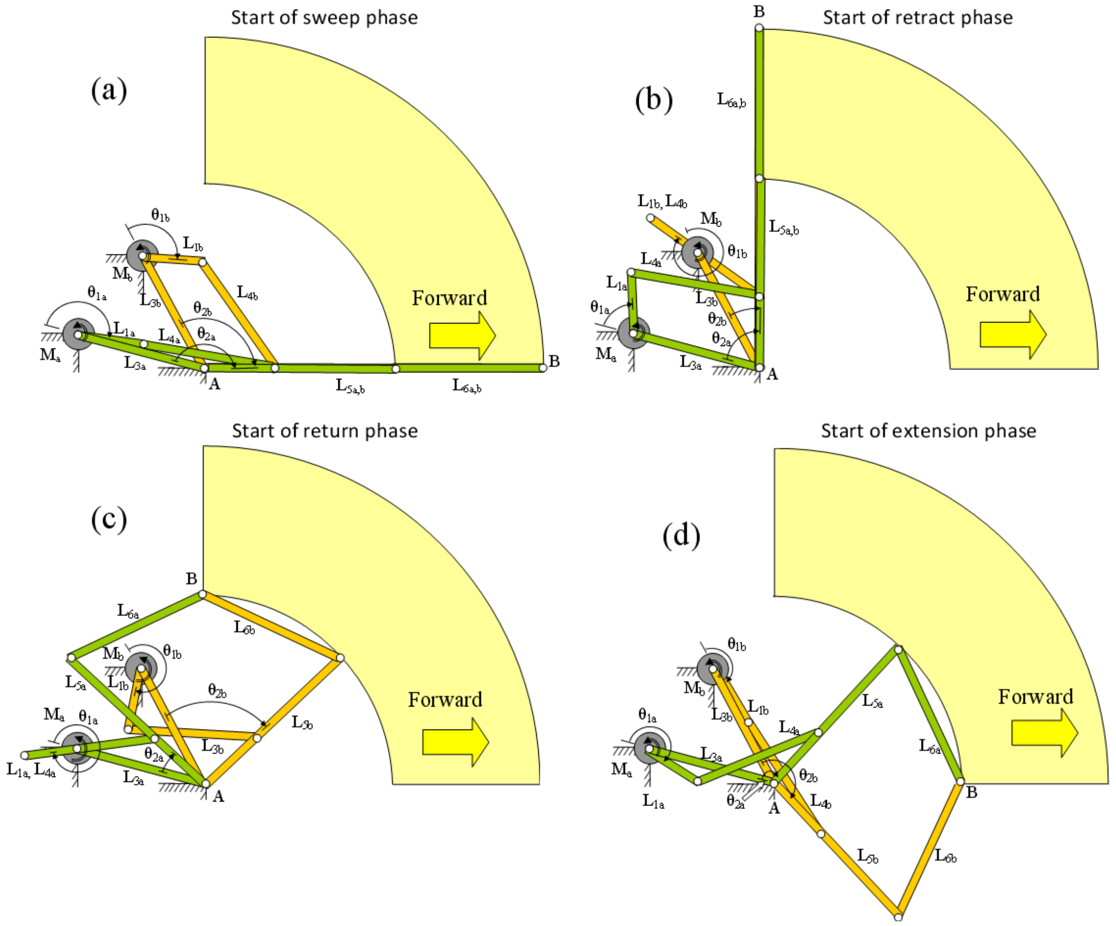

Figure 8: Link positions for workspace key points

3.2. Experimental implementation of digging mechanism

The mechanism was constructed using aluminium links containing roller bearings at each joint. Link length values were analytically selected for the experimentally constructed sweep-extend mechanism to create the desired rocker movement range, based upon the workspace parameters and physical size limitations of motors and gearboxes. The desired workspace parameters were W_i = 75mm, W_o = 135mm with a sweep angle of R=90°. Therefore, lengths $L5$ = 75mm and L_6 = 60mm. The minimum (θ_{2min}) and maximum (θ_{2max}) output rocker angle of the four bar linkages can be calculated to be 26.26° and 164.35° respectively resulting in an output rocker range (θ_{2range}) of 137.09°. The physical size of the motors/gearboxes and space for the mechanism to operate, resulted in a crank length (L_1) = 25mm and the fixed length (L_3) = 52mm. The remaining lengths were then calculated as using the four bar design process [23] resulting in L_2 = 27mm, L_4 = 52mm. These lengths are sub-optimal due to limitations in the physical hardware, but provide the correct movement range and acceptable performance [24].

Figure 9 shows the final experimental system constructed using two arms actuated by sweep-extend mechanisms. Each constituent four-bar mechanism is driven by a pair of Maxon A-max 32mm diameter 15 Watt DC motors through both a Maxon 66.2:1 32mm diameter Planetary Gearbox and an Ondrives E20 1:1 Crossed Axis Helical Gearbox (to change the axis of rotation). Connected to the motors are Maxon HEDL 5540 3 channel optical encoders used for position measurement along with continuous rotation potentiometers to set the initial angular position. The motor and mechanism parameters were selected so that an output force of 50N can be exerted at full extension (a torque of 7.8Nm at 0.135m). All other mechanical hardware components were designed and custom made for the application. Each arm also contains a 'blade' mounted on linear slides. The linear slides guide the blade to lie along the L" line so that normal forces can be applied– this is a specific addition for this robot application that does not affect the sweep-extend mechanism. A Measurement Computing PCI-QUAD04 4 channel quadrature encoder board is used to read the signals from the optical encoders. Additionally, a PCI-766-16 analogue output board and PCI-730-E analogue input board are utilized. These boards are interfaced with National Instruments Labview 7.1 to allow control to be implemented. Two videos of the mechanism operation are available online; a close up of the mechanism [26] and an illustration of mechanism dexterity [27]. Note the illustration of dexterity is performed by direct user control, this is not performed or required for the application proposed here.

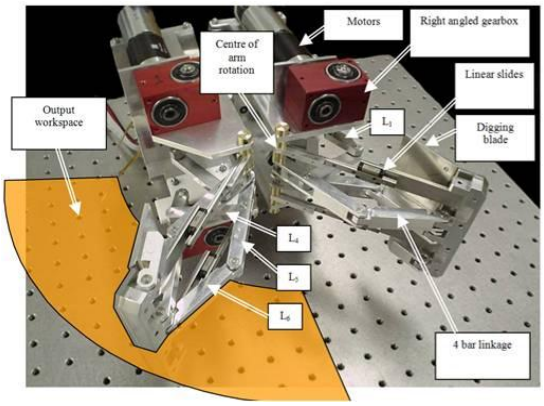

Figure 9: Mechanisms on fixed base

3.3 The mobile base

A mobile base is required to mount the digging system on. The requirements for the mobile base are:

- Smaller cross sectional area profile than the digging end effectors
- Flexible to enable locomotion through densely cluttered environments
- High traction to provide as large as possible tractive force to the digging end effector

There are two primary types of locomotion methods for mobile search and rescue robotics i) tracked vehicles, ii) wheeled vehicles. Tracked vehicles provide exceptional traction through large track contact area. However, they experience difficulty maneuvering in confined spaces due to the requirement for a relatively long and rigid length of track. Hirose [7] proposed 'mini' sections of track actuated relative to one other through linear actuators. This method of locomotion is likely to be ideal for the proposed burrowing robot.

A mobile platform was constructed to evaluate the performance of the digging end effector. Wheel modules consisting of two wheels driven by independent electric motors were attached in series to a rigid platform. Figure 10 (a, b) illustrate the individual modules with and without wheels. The modules use motors side by side to minimise their size and spur gears to allow concentric drive wheels.

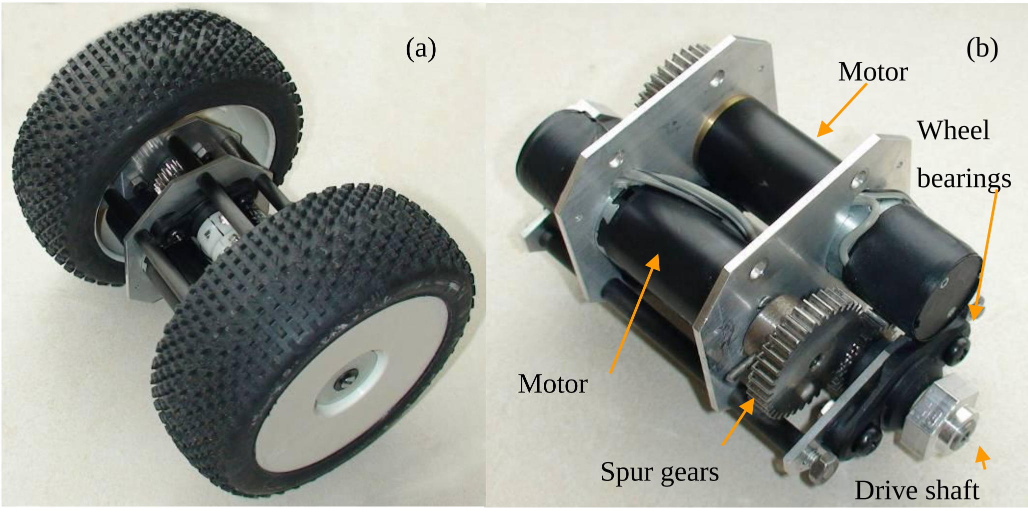

Figure 10: Wheel modules for the mobile robotic base (a) with wheels attached (b) without wheels

To test the performance on a mobile robot, a demonstrator was created based around ten independently driven wheels mounted in two rows of five (figure 11). Each wheel was driven by a Maxon Amax22 motor and 372:1 ratio gearbox. In this arrangement the demonstrator was able to drive forwards/reverse using skid steering; the long length and thin width are not optimal for a skid-steer system, however the performance was sufficient for a lab based environment.

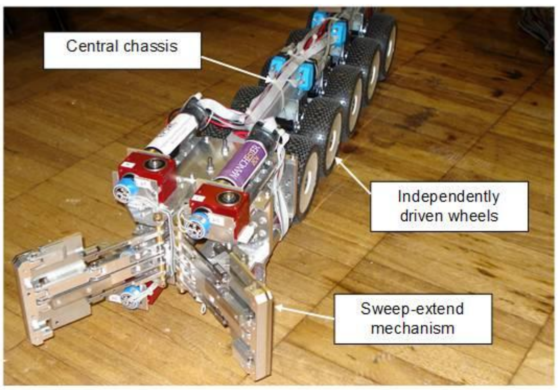

Figure 11: Mechanisms on mobile platform

The mobility of the demonstrator was designed to test the interaction of mobility and the mechanism and is not suitable for an actual search and rescue environment. The next step in the development of the mobile platform is to add active articulation between modules to enable the platform to bend and flex as a snake. A deployable prototype would require dust shielding and body streamlining to work in harsh conditions such as USAR.

4. EXPERIMENTAL TRIALS

The mechanism performance was initially evaluated on a fixed base to implement the controllers and test the interaction with objects. The mobile mechanism was then tested and evaluated by attempting to tackle the debris scenarios.

4.1. Fixed base

Figure 12 illustrates the fixed base test rig for the mechanism. A loading test was performed by placing a brick in the path of the mechanism. A video of the mechanism moving the brick is available online [28]. The static coefficient of brick on Medium-Density Fibreboard (MDF) is approximately 0.3, therefore it takes around 6N of force to overcome the friction on a 2Kg brick. The exerted force is around 10% of the mechanisms capability; these tests were conservative to protect the mechanisms from damage.

Figure 12: Loaded mechanism

Figure 13 shows both the loaded and unloaded motion trajectory. The stars drawn on the figure illustrate the point at which the loading commenced and finished. It is clear that the loading had a negligible effect on the trajectory tracking.

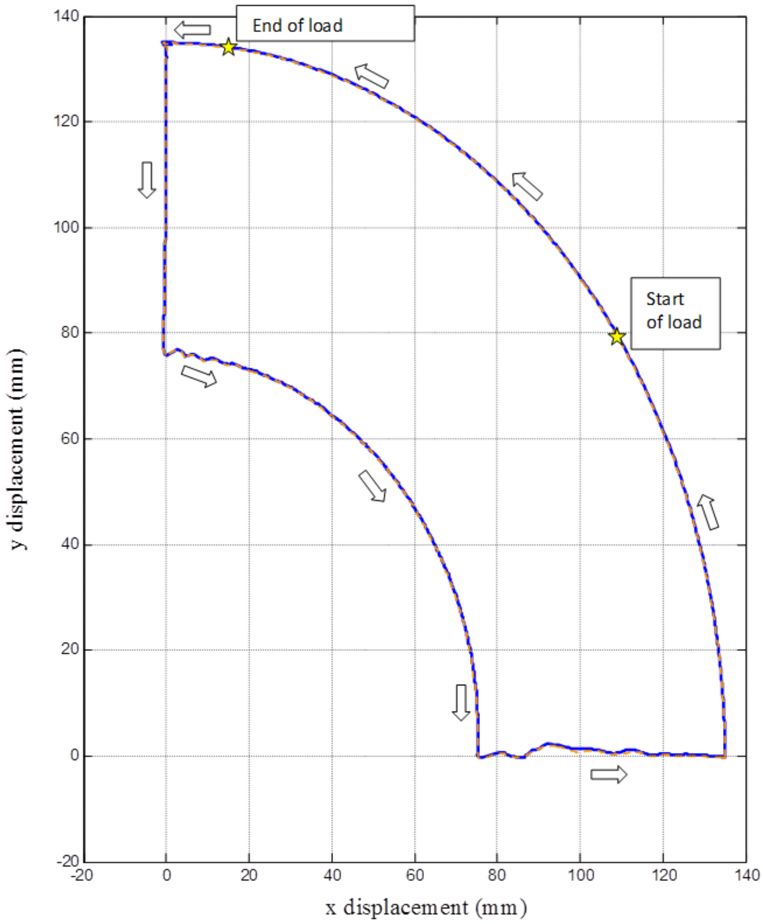

Figure 13: Loaded Trajectory

Figure 14 shows the unloaded and loaded control signals for both motors. An increased control effort for the period of loading is clearly visible. The additional control signal, distributed across both arms, is approximately 10% of the maximum control signal – confirming the predicted loading. The mechanism control signal is negative as the motors are rotating against the sign convention to produce the desired motion. A non-zero control signal is constantly required to overcome friction within gearboxes and joints. The spikes in the control signal are at the tips of the workspace, where mechanisms are required to move quickly to maintain the desired motion velocity (a property of the four bar mechanisms).

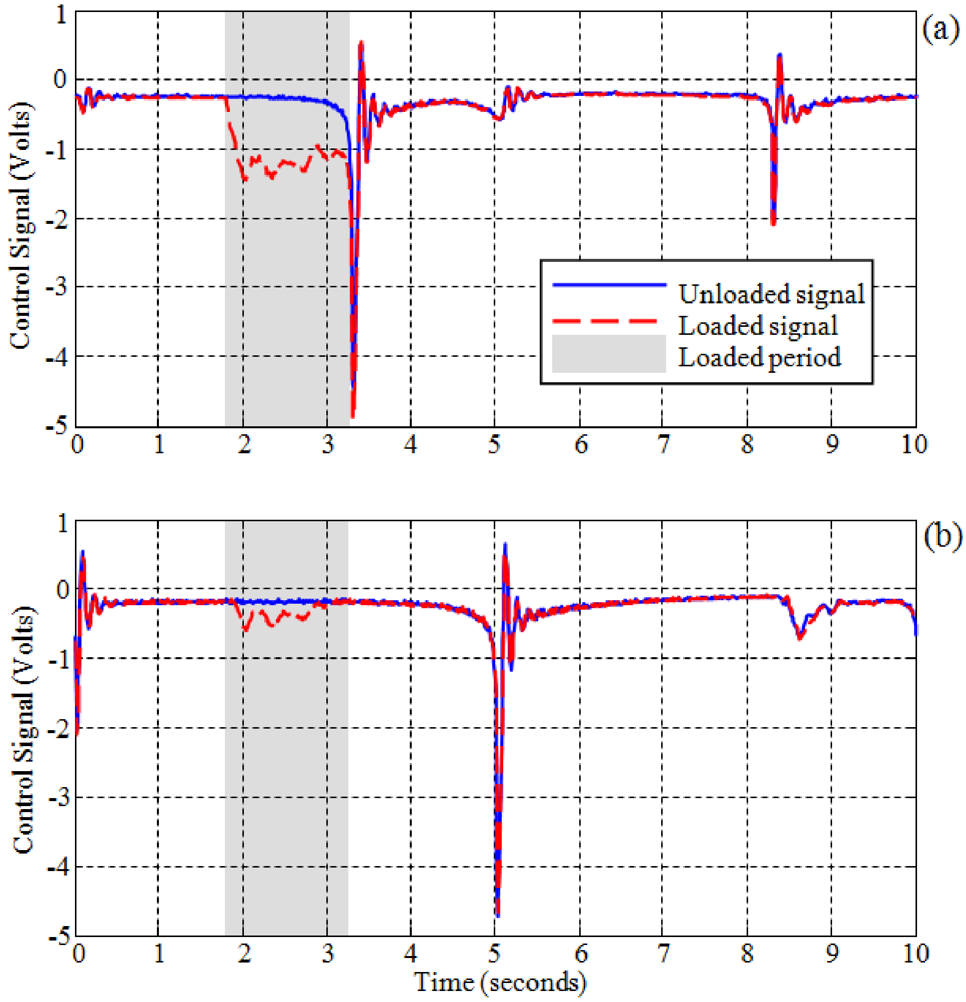

Figure 14: Loaded and unloaded a) upper and b) lower control signals

4.2. Mechanism on mobile base

The mechanism performance was tested on the mobile base. The system was controlled by a human operator (not associated with the robot development). The mechanisms were pre-programmed to continually perform full extend burrowing motions. The operator was able to pause the burrowing motions, manually operate each arm (input sweep and extend parameters, not directly control each motor), limit the maximum force output of each arm and control the movement of the mobile base.

Within these trials the operator was able to view the motion of the mechanism from a viewpoint above and behind the robot to pause or restart motion. The ability to pause the motion allowed faster forward motion of the mobile base when no objects were in front of the robot (i.e the mobile base can drive forward more than one mechanism workspace per cycle).

This view point would not be realizable in reality, and the operator would use cameras facing forward and attached to the mid-point of the robot body facing the digging arms. This would provide a view sufficient for pausing and restarting motion. If the operator did not have a clear view, the mechanism could be left in cyclic mode and would automatically move objects in the robot path if the base moves forward one workspace at each cycle.

Scenarios similar to those proposed (in section 2) were experimentally created. The demonstrator mobile mechanism does not have the capability to travel over rough terrain; therefore scenarios A and B were modified to be accessible at ground level.

Scenario A

The experimentally constructed scenario A focused on the manipulation of hanging cables. The task requires low forces, but relatively high manipulator dexterity. A video of this scenario is available online [29]. The scenario seems a trivial task, however it is likely that a single cable would block the progress of most, if not all, current search and rescue robots. While the cables are not under tension, attempting to drive through them can result in entanglement with the robot and hence cause tension. The operator was able to manipulate the wires and move them to the side while the robot moved past.

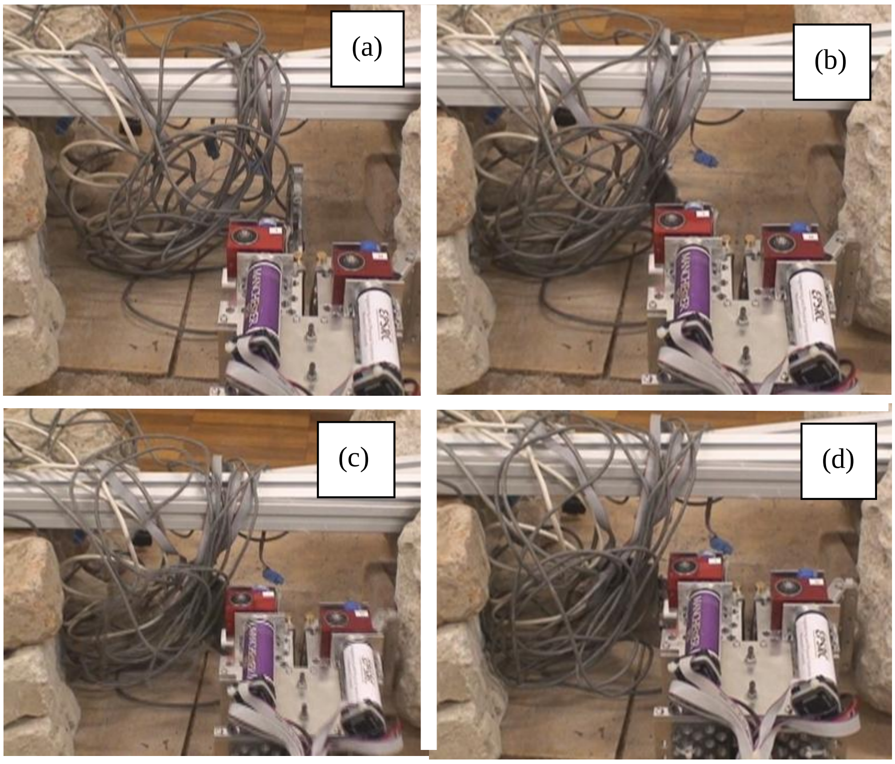

Figure 15: Manipulation of wires

Figure 15 illustrates manipulation of wires, (a) the robot path is blocked by free hanging wires (b) the left digging arm starts to push the wires to one side, (c) & (d) the wires are moved to the side of the robot body. The task was performed three times with the robot controlled by the same operator. On average this task took 42 seconds and required a single cycle of the mechanism.

The current system requires a streamlined shell for the mechanism and body work as in this prototype the wires become caught on protruding components if the robot attempts to drive through. The originally defined scenario, including passageways at raised heights has not been achieved and remains an extreme challenge for robot development. However, the mechanism has demonstrated useful capabilities if combined with streamlined bodywork.

Scenario B

The experimentally created scenario B used concrete pieces from a local demolition site and pieces of intermingled wood. A video of this scenario is available online [30]. The operator initially attempted to bulldoze through the debris, with the mechanism parked in a forward facing pose. The attempt resulted in more tightly packed debris and the motion completely blocked. This is an interesting result in itself that demonstrates the need for manipulators on mobile robots. After several attempts the operator resorted to a more controlled approach where individual pieces were manipulated out of the passageway.

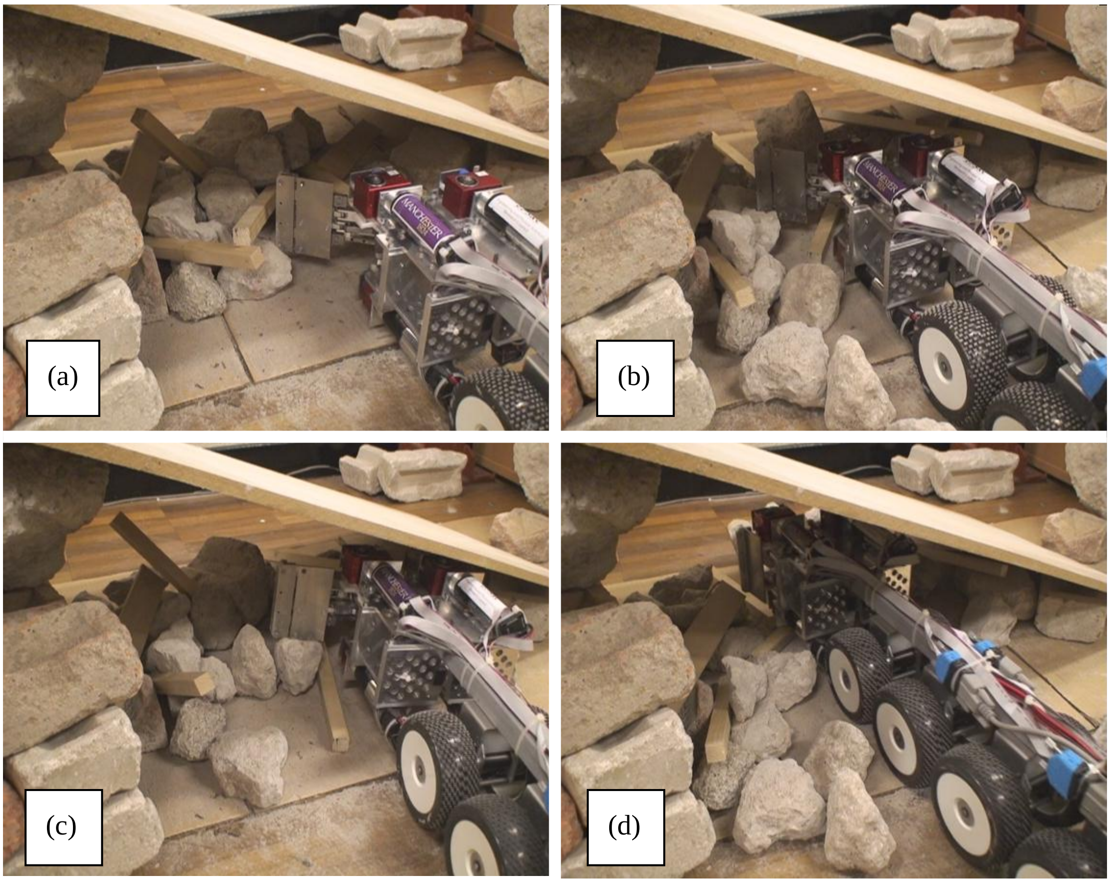

Figure 16: Manipulation of wood and concrete in a lean to collapse

Figure 16 illustrates the manipulation of the debris (a) the robot approaches the debris pile, (b) the digging arms manipulate the debris to one side (c) the forces applied by the digging arm force the robot into the lean to collapse structure resulting in the operator driving out and then back in (d) a path has been cleared of concrete and the wood is driven over. Interestingly the operator controlled the vehicle to couple the manipulator motion with the robot motion – i.e. when the manipulator was pushing the debris to one side the vehicle was reversed to pull the debris backwards. Using this technique the operator was able to substantially increase the removal of debris at each stroke. When only a few pieces of debris remained, the operator returned to the 'bulldozer manoeuvre', this time with success. The task was performed three times with the robot controlled by the same operator. On average this task took 367 seconds and required 16 cycles (counting the motion of the left and right mechanism as separate cycles). This test highlighted limitations in that small debris (e.g wood) passes under the digging arm clearance and that if large forces are applied the robot body can be pushed against debris.

Scenario C

Scenario C requires the removal of densely packed large pieces of debris, full size brick and similar concrete size pieces. The configuration is an extreme test for the mechanism force capability; the similar size pieces tended to interlock and form impassable blockages. Seemingly identical movements resulted in different outcomes in the movement and structure of the debris. The robot was not able to reliably perform this task. Therefore, the scenario still presents significant challenges and it is unlikely this mechanism is capable of reliably working in this environment due to the required forces.

Scenario D

Scenario D is based around smaller pieces of concrete debris that are more likely to flow when forces are applied. A video of this scenario is available online [31]. This scenario still presented significant challenges, but required less force than scenario C. The operator again chose to couple the arm motion with the forward and reverse motion of the vehicle. In Figure 17 (a) & (b) the digging arm is pushing a half brick to its side, (c) & (d) smaller pieces of concrete arm moved from the robot path. The smaller pieces of debris allowed the operator to scoop many pieces at once and pull them out by reversing the robot. Often one arm was used to support the vehicle against the side of the opening and allow greater forces to be applied to the debris than would be allowed by the vehicle weight and friction coefficient alone. The mechanism successfully completed the experimental task. The task was performed three times with the robot controlled by the same operator. On average this task took 448 seconds and required 18 cycles (counting the motion of the left and right mechanism as separate cycles).

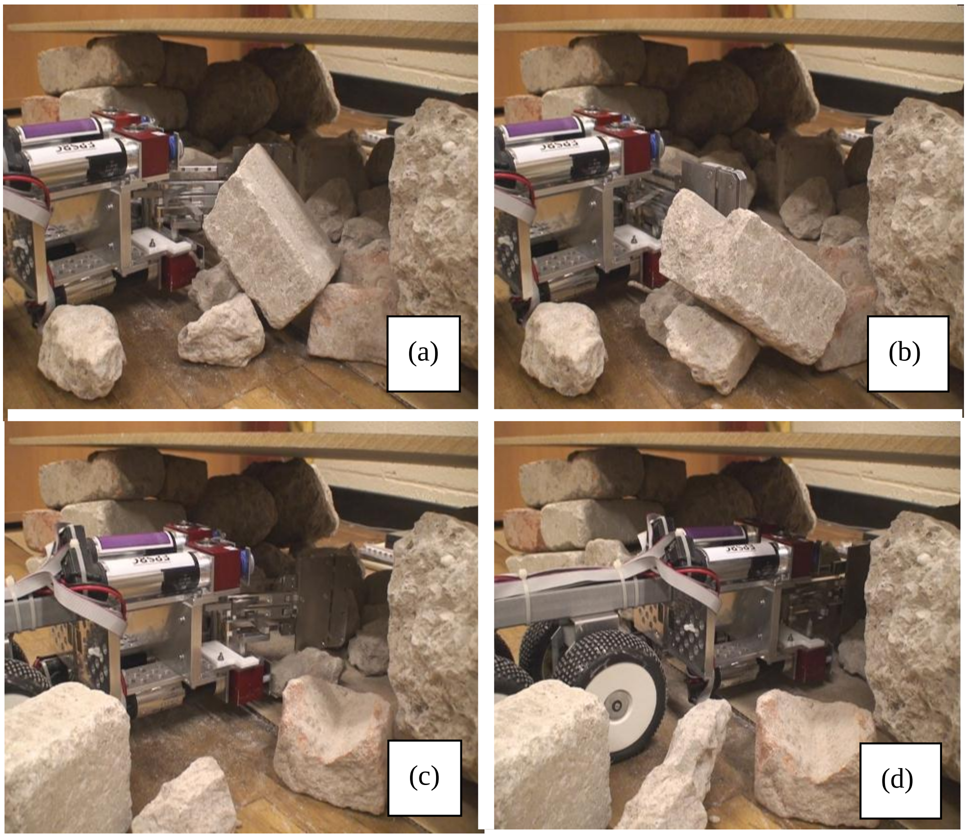

Figure 17: Manipulation of half bricks and concrete

Scenario E

This scenario was designed to be an extreme test of burrowing performance. The mechanism would fail a full trial of this scenario (as described in section 2) due to the lack of debris shielding. However, a modified test was created to demonstrate the flow of debris around the mechanism. The fixed base mechanism was surrounded with fine polystyrene packing material and basic dust shielding. In this trial, the mechanism was mounted on a fixed base as forward motion of the robot would confuse the analysis of debris flow due to the end effectors. The left hand diagram (Figure 18) shows the initial condition of debris surrounding the robot. The middle diagram shows the debris position after 2 cycles of motion taking 38 seconds. It is clear that some of the debris has moved from the nose of the mechanism to its side. The last diagram overlays an image of the initial debris field with an outline of the debris position after the two cycles of motion. This clearly shows how the debris has been pushed to the side and behind the mechanism. Although the polystyrene is relatively easier to move than densely packed sand, dust and mud, the final debris position after a couple of cycles shows the ‘flow’ of material to the side of the robot, and is typical of a burrowing scenario.

Figure 18: Flow of material around device

5. CONCLUSIONS

A mechanism termed *the sweep-extend mechanism* has been developed for mobile search and rescue robots. The mechanism was trialed on a fixed base and a mobile robot. The trials on the fixed based demonstrated good controller performance in the presence of external loads. The mobile mechanism was tested against a specification through five challenging scenarios that maybe encountered in USAR robotic deployment. The mechanism was demonstrated to have the excellent dexterity, the required workspace and the specified control performance. The remote centre of operation principle worked well and the cyclic motion achieved through motors rotating in a constant direction was successful. The forces met the specification, but occasionally the required practical force exceeded the specified force and the robot was not able to move the debris. In particular, scenario C is an extreme test requiring output forces that often exceeded the force available due to interlocking bricks. This scenario is very difficult to overcome as the additional forces required to move the bricks would result in a larger robot that requires more bricks to be moved; hence a robot with higher force density is required. The mobile wheel modules were fixed inline and hence the robot was not able to drive over loose debris and was unsuccessful in meeting the mobility specification. The scenarios were modified to compensate for the mobile platform's inability to traverse uneven terrain.

Several interesting results were obtained and in particular the new concept of coupling the mechanism motion to the motion of the overall vehicle. Optimising the mechanism links to reduce the system weight and incorporation onto a more capable mobile robot are the next steps towards the system development.

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[29] Video of Manipulating wires: http://lutube.leeds.ac.uk/menrcr/videos/5956

[30] Video of Lean to collapse: http://lutube.leeds.ac.uk/menrcr/videos/6089

[31] Video of Pancake collapse: http://lutube.leeds.ac.uk/menrcr/videos/6090