A Novel Design for a Robot Grappling Hook for use in a Nuclear Cave Environment

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Abstract: Within the field of robotics there exist few designs for detachable grappling hooks. This paper focusses on the novel design of a detachable grappling hook for use within a nuclear cave environment. The design seeks to exploit the complex network of pipes that is present within a nuclear cave. It is hoped that the grapple may be used to aid with mapping and characterisation of the nuclear cave, as well as increasing the movement capabilities of robots within the cave. It is shown that our prototype grapple is able to support on average 2.4kg of mass, or thirty times its own weight. In addition when dropped from a height of 7.5cm, which removes ballistic instability, the grapple is able to engage itself 87% of the time. Finally the minimum speed that the grapple must be travelling, in order to secure itself to its target, is found to be 1.08m/s.

1. INTRODUCTION

The requirement for nuclear decommissioning is becoming increasingly prevalent as more nuclear facilities are coming to the end of their operational lifetime. A particular problem during the decommissioning process is the nuclear cave. This is an area of a nuclear facility which much of the key pipework is routed through, and typically contains multiple pressure vessels. The desire of the nuclear industry is to use an autonomous robotic system to characterise the nuclear cave environment in order to make safe disposal of its contents possible.

As can be seen in figure 1, the nuclear cave environment presents a challenging environment for mobile robotic systems to move around in. Aside from the obvious difficulty in moving through the complex network of pipes and pressure vessels, the floor of the nuclear cave presents its own obstacles. Robots seeking to traverse the floor of a nuclear cave will encounter: slumps and channels on the floor of the cave; debris from previous excursions into the cave; unknown floor geometry; leakages caused by damaged pipe work, and inclined floors. Finally any robot seeking entrance to the nuclear cave must normally be capable of fitting through a hole 15cm (6 inches) in diameter, as this is the standard entry hole size.

Small wheeled ground robots make for a useful tool for characterisation within the nuclear cave. This is because they provide a stable platform on which an array of sensors may be placed; they have good energy efficiency, mission duration and payload capacity when compared to flying robots; and they can be miniaturised to fit through the 15cm entry hole. However when reducing the size of a robot the size grain hypothesis states: "as a body gets smaller it becomes more difficult for it to overcome obstacles due to their increase in relative size" (Noh et al. (2012), Zhou et al. (2005)). Thus a small robot moving around the cluttered nuclear cave environment is likely to encounter unsurmountable obstacles.

As a robot in a nuclear cave environment is likely to meet multiple obstacles during its mission, a supplementary locomotive modality becomes useful. This would enable the robot to access areas of the cave which would be inaccessible to a typical ground robot. There have been various studies into possible supplementary methods. One such modality is the use of small robotic hopping robots (Noh et al. (2012), Zhou et al. (2005), Sugiyama et al. (2005), Armour et al. (2007), Lambrecht et al. (2005), Stoeter et al. (2005)). A further interesting method is the use of wings to increase the speed and efficiency of ground robots (Peterson et al. (2011)). However, this paper focusses on the design and use of a grappling system to provide additional movement capabilities within the nuclear cave, and to assist with characterisation.

The grappling hook provides several useful features for the characterisation of a nuclear cave environment. The first of these is that it may be used to surmount obstacles present within a nuclear cave. A grappling hook would allow for the robot to make use of the intricate network of pipes to pull itself over channels, sumps, leakages and debris in order to continue mapping otherwise inaccessible areas. In

Fig. 1. Shows the nuclear cave environment, which poses a difficult characterisation task for decommissioning.

addition, the use of a grappling hook allows for a bird's eye view of the environment, which could be useful for mapping. Finally the slow ascension that can be offered by a grapple could be utilised for mapping. This could be used to perform a scan of the environment as the robot pulls itself up, allowing for three dimensional mapping of the upper areas of the cave.

The downside of traditional grappling hooks is that they are not easily detached once engaged with their target. This would not suit a mobile robot as it means that only one obstacle may be overcome. One possible solution is to carry multiple hooks, though this has the downside of additional weight, and a larger size. A more elegant solution is a detachable grappling hook.

There exist few designs for robotic grappling hooks, and for detachable grappling hooks, even fewer. One example is the Scout mobile robot platform (Drenner et al. (2002b,a)), this utilises an external spring launching mechanism with a large spiked grapple. Such a design is not detachable and currently is not able to be loaded automatically. An easily implemented method for detachable grappling hooks is exemplified by the 'HandBot' from the Swarmanoid project (Dorigo et al. (2013)). This utilises an electromagnetic grapple which may be easily switched on and off. However, within the nuclear cave environment there are few ferromagnetic surfaces so this method for grappling becomes less useful. Several interesting designs for detachable grappling hooks are explored in (Asano et al. (2010)). The first of these designs features a gripper

at the end of the line, however if the gripper does not collide with the target in a specific orientation, it cannot grip it. The second design features a clamp. This is able to latch to cyclindrical pipework and is the design most akin to that presented in this paper, however it was found that the design was too heavy to be launched reliably. The final design presented in (Asano et al. (2010)) features an extendible hook. This features a bend that can be fully extended by a wire in order to detach from its target, though this is too large for use in a nuclear cave. A final method for grappling that has been explored it to use pre-installed tether points to hook onto (Stepan et al. (2009), Fearing (2013)). However, as the nuclear cave is inaccessible to humans the installation of such points becomes difficult.

Though this paper focusses on the use of the grapple for the mapping of a nuclear cave environment, there exist multiple other uses for such a design. One potential use is in the efficient erection of scaffolding. If the hook were attached to a piece of already secured scaffold, it could be used to move items from the ground to the top of the construction quickly. In addition the grapple could be easily adapted for use on tree branches. This could permit uses such as robotic traversal of forest area, or aid in forest construction tasks. As the design of the grapple allows detachable attachment to most cyclindrical surfaces, it is likely there are many more potential uses.

Overall, within robotics, it appears there is a paucity of detachable grappling hooks that could be used within a nuclear cave environment. This paper focusses on a design that is specific to such an environment, but that could be used in other areas where there is a large quantity of pipework, or cylindrical infrastructure.

The structure of the paper is as follows. First the design of the grappling hook will be outlined. This will be followed by an explanation of the experimental methodology used to examine the quality of the design. The results of these experiments will then be presented, with a discussion of the results in the subsequent section. Finally conclusions will be drawn.

2. DESIGN AND METHODOLOGY

2.1 Design

As can be seen in figure 1, the nuclear cave contains a complex network of pipes. These pipes make an excellent target for a grappling device. Previous work exploiting the nature of pipe and scaffold networks has focussed on either gripping the pipe work with an end effector (Zhou et al. (2005)) or surrounding the pipe with a platform able to travel along it (Aracil et al. (2003)). To the knowledge of the authors, there has been little or no work investigating the design of a grappling device that could be used in such an environment.

When designing the grapple the following requirements were considered:

(1) **Grip size** - The grapple should be capable of clasping pipework of diameter 40mm and below.
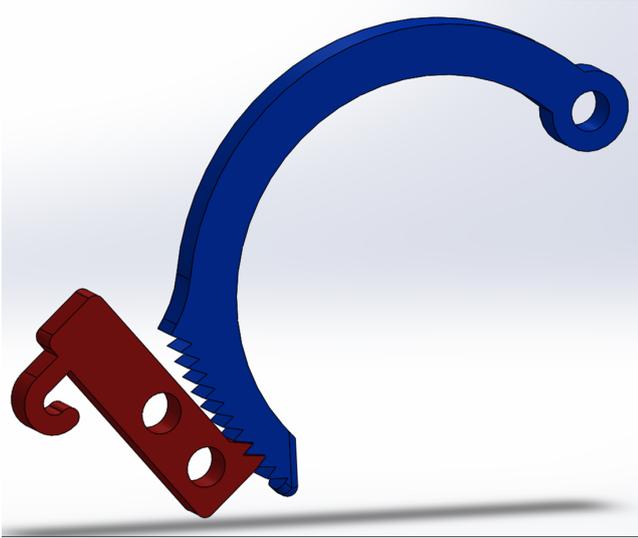(2) **Grapple mass** - The grapple should be lightweight (100g or less) so that it may be easily launched.

Fig. 2. Shows the design of the ratcheted swivel (right) and the lock pin (left) that are used to secure the grapple to pipe work.

(3) **Mass held by grapple** - The grapple should be capable of supporting a small robot, in this case the Foot-bot from the 'Swarnoid' project was chosen as a reference Dorigo et al. (2013). This corresponds to a mass of 1.8kg.

(4) **Detachability** - The grapple should be detachable, preferably remotely.

The grapple's design is similar to that of a hand cuff. This utilises a ratcheted swivel and lock pin, shown in figure 2, to secure the device to the pipe work. The device features a semi-circular recess that is used to encapsulate the pipe in cooperation with the ratcheted swivel, with radius 22mm to fulfil requirement (1). Currently to release the device a small lever is utilised, however in future it is to be released using a solenoid switch, in order to better fulfil requirement (4). The lock pin is tensioned by a spring in order to prevent the swivel from releasing. The tension in the spring is varied through the use of an adjustable screw, this is to enable the force required to engage the swivel to be changed. As the locking mechanism currently protrudes from the side of the grapple, a counter weight has been added on the opposite side. This is to encourage the grapple to stay level whilst in flight and once it has collided with its target. The final mass of the design was 80.86g, this is in keeping with requirement (2). Two dimensional technical drawings can be seen in figure 3, with a three dimensional rendering in figure 4.

Both the main body of the grapple and the ratcheted swivel were created using a 3D printer. The other parts shown in figure 4 were laser cut from 3mm acrylic. The grapple was then assembled using screws to secure the side panels to the main body, in addition screws were used as pivots for the lock pin and ratcheted swivel.

When the grapple collides with a pipe, or other cylindrical target, the swivel is made to rotate. The swivel then enters the locking system, described above, which allows rotation to occur in only one direction. Due to this the grapple is
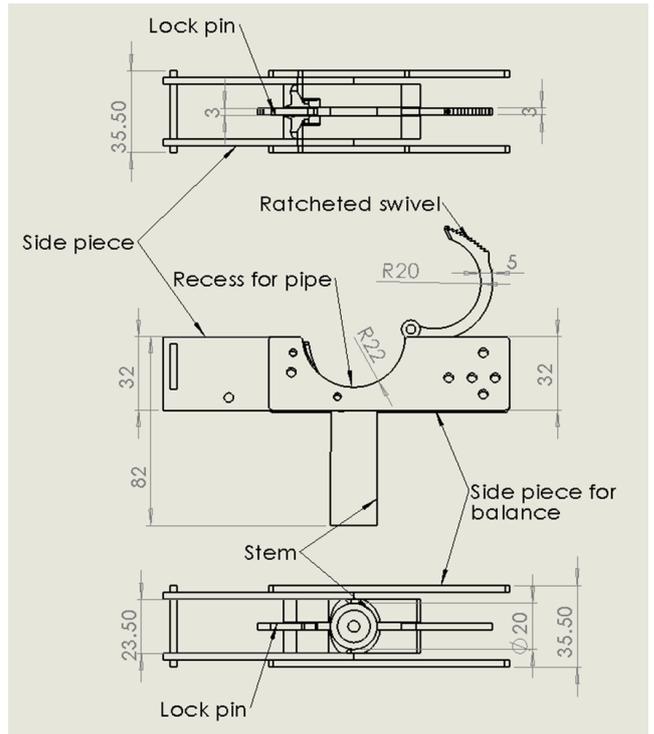

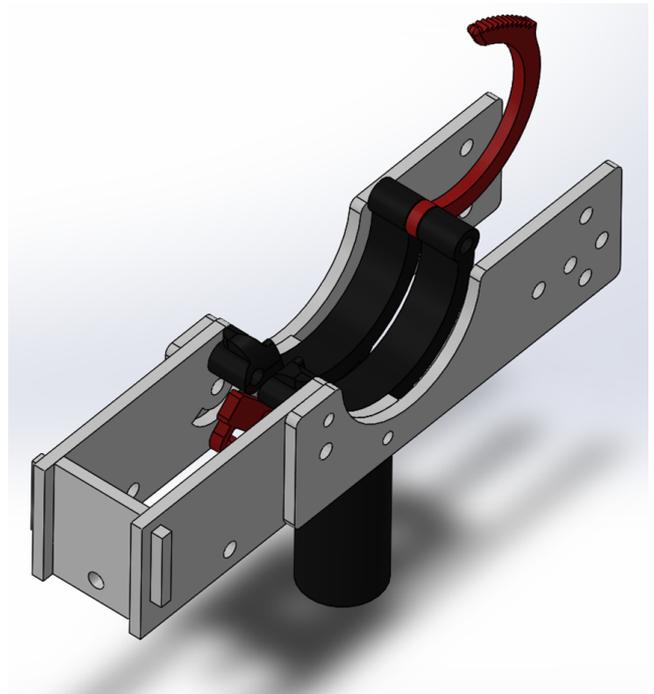Fig. 3. Shows the design and dimensions of the grapple in 2D.

Fig. 4. Shows a three dimensional rendering of the grapple's design. The red components show the locking mechanism, comprising of the ratcheted swivel and lock pin. In black the main body of the grapple is shown. Finally in white, the support (left) and balance (right) side and back pieces are shown.

secured to the pipe in a manner analogous to a hand cuff on a perpetrator's wrist.

2.2 Experimental Method

The performance of the grapple is to be examined through two criteria: the maximum mass it is able to support and the consistency with which it is able to attach. These were chosen as the most important test criteria due to the need to support a robot's weight and the need to reliably grapple during operation. In addition the minimum speed required to initiate grappling was calculated.

To conduct the maximum mass test, a section of pipe 40cm long and 2.5cm in diameter was suspended at a height of 30cm using a clamp and clamp stand. The grapple was then latched in its fully closed position (all teeth engaged). Weights were then attached to the grapple using a slotted mass set with a hook. The weight was increased in increments of 50g until the grapple was no longer able to remain secured. At this point the maximum weight held was recorded and the test repeated. The test was repeated 30 times in accordance with the National Institute for Standards and Technology (NIST) guidelines for statistical significance. The NIST test document stipulates "30 repetitions to demonstrate statistical significance to at least 80% reliability with 80% confidence" (Jacoff (2009)).

In order to test the consistency of attachment it was decided that the grapple would be dropped, rather than launched. This allows both reliable repetition, and a more accurate calculation of minimum activation speed. In addition, it allows experimentation to focus on the quality of the grapple's performance, rather than compounding errors caused by any potential launching mechanism. Test apparatus was established to consistently drop the grapple. The first part of this apparatus was comprised of a clamp holding the same section of pipe used in the mass test, suspended at a height of 15cm. A wooden rig, with a cavity drilled for the stem of the grapple, was secured above the section of pipe. The rig could have its distance from the section of pipe altered, along with its angle. The consistency of attachment was assessed from five different heights: 7.5cm, 10cm, 12.5cm, 15cm and 17.5cm. This height was measured from the base of the wooden drop rig. At each of these heights the grapple was dropped onto the pipe. If the grapple was able to engage and hold itself in place then a success was recorded, if instead it fell, a failure was recorded. Thirty iterations were completed at each height, in keeping with the NIST test criteria. The three dimensional layout of the test apparatus is shown in figure 5, with a two dimensional illustration accompanying it in figure 6.

To determine the minimum speed required for attachment, the minimum height that the grapple could attach from first had to be determined. The same test apparatus shown in figure 5 and 6 was used to progressively lower the height of the grapple, until it was just able to secure itself to the pipe. From this height the speed of the grapple could be determined using:

$$v = \sqrt{2gh} \qquad (1)$$

where v is the minimum speed, g is acceleration due to gravity and h is the minimum drop height.
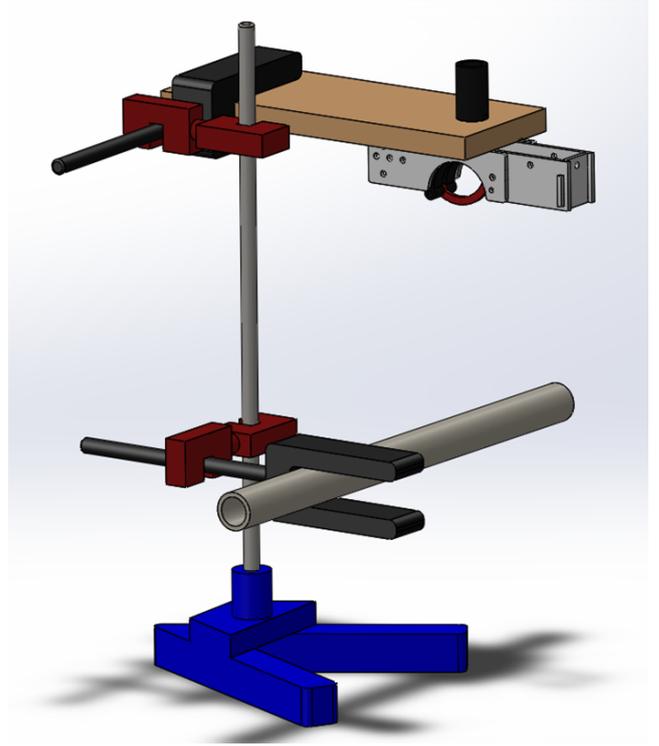

Fig. 5. Shows the 3D layout of the test rig used for the consistency verification.
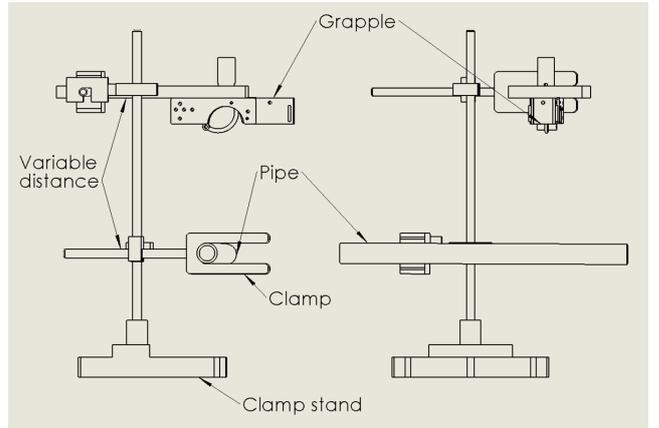

Fig. 6. Shows the 2D layout of the test rig used for the consistency verification.

3. RESULTS

In the thirty repetitions it was found that the maximum mass that the grapple was able to support was 2.65kg. The lowest mass that a failure was recorded at was 2.2kg. The average mass held across the thirty tests was 2.4kg. The grapple has a weight of 80.86g, thus its average capacity is approximately thirty times its own weight. In addition the results from this experiment show that design requirement (3) has been kept to; this stipulated that the mass held should be 1.8kg in order to be capable of supporting a small robot.

Whilst conducting the consistency test it was found that the apparatus would slightly misalign due to impact of the grapple. Thus every ten repetitions of the drop test

the apparatus was realigned, until the thirty trials had been completed. The results from the five drop heights are summarised in table 1.

Table 1. Shows the results of the consistency investigation

Drop Height (cm)	Successful Engagements	Percentage Success
7.5	26/30	87%
10	19/30	63%
12.5	20/30	67%
15	19/30	63%
17.5	3/30	10%

The minimum height which the grapple was able to secure itself from was found to be 6cm. This means that the minimum speed required to engage the grapple is:

$$v = \sqrt{2gh} = \sqrt{2*9.81*0.06} = 1.08m/s \qquad (2)$$

The results have been presented in this section. In the next section the significance of these results will be discussed alongside suggestions for future work.

4. DISCUSSION AND FUTURE WORK

On average it was found that the grapple could support a mass of 2.4kg, or thirty times its own weight. The grapple was able to comfortably sustain a mass of 2kg. This means that a robot weighing 2kg or less could suspend itself from such a grapple in a nuclear cave environment. Suspension would require little energy and enable the robot to gain a birds eye view of the environment. In turn this would enable a more detailed three dimensional map of the nuclear cave to be generated. In addition, the robot would be able to pull itself over larger obstacles by either initiating a pendulum motion, or through the use of multiple grapples for brachiation.

The investigation into the consistency with which the grapple was able to engage with its target gave interesting results. Dropped from a height of 7.5cm the grapple was able to achieve an 87% success rate. This shows that the basic design of the grapple is suitable for grasping onto pipework. This rate of success is likely to be the result of a combination of the grapple having obtained its minimum success speed, coupled with a predictable and consistent ballistic stability.

At heights of 10cm, 12.5cm and 15cm the grapple was able to maintain a consistency of around 65%. This drop in performance appears to be due to the uneven weight distribution of the grapple. This weight distribution is caused by the locking mechanism, which protrudes from the side of the grapple. Attempts were made to counter this instability with the addition of the counterweight side panels. However this was not enough to remove the turning affect produced whilst the grapple was in flight.

At a drop height of 17.5cm the grapples consistency fell dramatically to 10%. This is because, as the grapple fell, the turning motion produced caused the target to fall to one side of the grapple's recess. This meant that the swivel did not pivot around its axis fully, and prevented the locking mechanism from becoming secured.

The results of the consistency examination provide proof of concept. The grapple is able to repeatedly latch on to pipework and thus has the potential to be utilised in a nuclear cave environment. However, the locking mechanism should be redesigned so that it falls in line with stem portuding from the base of the grapple. This would produce a centre of mass much closer to the centre of the grapple, thus stabilising the grapple during flight and enabling it to more successfully secure itself to its target.

Finally the minimum speed of the grapple required to initiate engagement with the target was found to be 1.08m/s. This speed serves as a requirement for future launching mechanisms that may be designed for the grapple. If this speed or greater is achieved at the point that the grapple collides with its target, then it is likely to engage.

Future work could focus on creating a launching mechanism, capable of achieving the 1.08m/s minimum engagement speed. This mechanism could then be installed on a robot under 2kg in order to assess the ability of a robot to utilise this locomotive modality.

5. CONCLUSION

In this paper the utility of a detachable grappling hook, for traversal of a nuclear cave environment has been described. The novel design of a grappling hook for use on pipework in a nuclear cave has been outlined.

It has been found that the grapple is capable of supporting a maximum load of 2.65kg, with an average of 2.4kg. In addition it has been shown the grapple is able to achieve a maximum engagement consistency of 87%, from a height of 7.5cm. The consistency fell to approximately 65% at heights of 10cm, 12.5cm and 15cm. The minimum consistency was found to be 10%, dropped from a height of 17.5cm. This is most likely due to low ballistic stability. The minimum speed required to engage the grapple was found to be 1.08m/s.

Future work could focus on the design of a launching mechanism capable of propelling the grapple at speeds upwards of the minimum 1.08m/s. In addition this launcher could be mounted on a robot weighing less than 2kg, and a guidance system implemented.

In conclusion, it has been shown that the grapple is capable of latching onto pipework. This result is promising for the use of such a grapple on the pipework present in a nuclear cave environment, enabling increased mapping functionality and obstacle avoidance.

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