A Robust Polyurethane Depositing System for Overcoming Obstacles in Disaster Scenario Robotics

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Abstract. One of the most difficult challenges for terrestrial robotic platforms in disaster scenarios is their inability to traverse highly irregular terrain. Many different robotic architectures have been proposed over recent years, each with benefits and shortfalls. In this work, we propose a Polyurethane Foam depositing system, which can be applied to any such platform and increase its ability to overcome obstacles significantly. The system proposed is inexpensive, and the way in which it overcomes obstacles allows very simple control systems for autonomy. The deposited foam has a potential expansion ratio of over 33× its constituent parts and a final compressive strength exceeding $2MPa$, final mechanical properties can be tuned on board. The system has been implemented on a two-tracked rover and its autonomous responses tested against significant objects and chasms. The results show that the amount of foam deposited can be well controlled and multiple layers can be stacked on top of each other to significantly increase altitude.

Keywords: Robotics · Disaster Scenario · Polyurethane Foam · Overcoming obstacles · Search and Rescue.

1 Introduction

1.1 Background

Disaster scenarios consider the environment or aftermath of an area post-event; where an event can typically be considered a sudden accident or a natural catastrophe that causes great damage or loss of life. Hundreds of floods, storms, heat waves and droughts have left over 600,000 people dead and 4.1 billion injured or homeless around the world since 1995, according to a U.N. report [4].

When a disaster strikes, it is often critical to find victims as soon as possible. People stranded after an earthquake or hurricane or who are living in a war zone are often stuck for days without food, water or medicines. They are usually cut off from the world due to collapsed infrastructure, making it hard for them to receive necessities. First responders are some of the most at risk in the relief efforts [1], often entering highly unstable areas with little knowledge of the interiors.

Recent advancements in technology are revolutionizing the roles of aerial, terrestrial and maritime robotic systems in disaster relief, search and rescue and salvage operations [6]. Robots can be deployed quickly in areas deemed too unsafe for humans and can be used to guide rescuers, collect data, deliver essential supplies or provide communication services. However, taking terrestrial robotic platforms from the often predictable even surfaces of a lab, to the highly irregular terrain present in disaster zone environments, presents one of their greatest shortfalls: overcoming obstacles.

Various robot architectures have been proposed for driving and climbing on rough terrain and the models can be divided into roughly five categories [2]: single-tracked, multi-tracked, wheeled, quadruped-platforms (or biologically inspired systems) and humanoid. The unique solution of each platforms results in particular benefits when overcoming obstacles. Hybrid platforms have been proposed to maximise the pros of their constituent architectures. Such products are often costly and their added benefits limited. A comparison of tracked, wheeled, humanoid and their respective hybrids was performed in [3] and is reported in Table 1. This overlooks quadruped and biologically inspired platforms as these represent a very diverse array of systems which are difficult to generalise.

Table 1. Synthetic comparison of locomotion system features, taken from [3]. LW = Legged Wheeled, LT = Legged Tracked and WT = Wheeled Tracked

	Wheeled	**Tracked**	**Legged**	**LW**	**LT**	**WT**
maximum speed	high	med/high	low	med/high	medium	med/high
obstacle crossing	low	med/high	high	med/high	high	medium
step climbing	low	medium	high	high	high	medium
slope climbing	low/med	high	med/high	med/high	high	med/high
soft terrain	low	high	low/med	low/med	med/high	high
uneven terrain	low	med/high	high	high	high	med/high
energy efficiency	high	med	low	med/high	medium	med/high
mechanical complexity	low	low	high	med/high	med/high	low/med
control complexity	low	low	high	med/high	med/high	medium

As can be seen from Table 1, no one platform architecture has so far proven to outperform the rest. As a result of this, projects have been put forward more recently to increase the abilities of platforms using material deposition. One such material is Polyurethane (PU).

1.2 Polyurethane Foam

PU is a synthetic resin in which the polymer units are linked by urethane groups; when combining the two part constituents (PU-5800, Polycraft), the mix quickly expands and then sets rigid. The final properties of the PU foam depend largely on the mix ratio and can be changed quite easily. Compressive strengths of over $2MPa$ are possible, which can easily support the weight of a human standing thereon. Also, potential expansion ratios of over 30× the original volume means it can generate $25dm^3$ of final structure foam from $840cm^3$ of the two part liquid constituents [5]. These values depend largely on the mixing style and have been recorded through testing on the system shown in Section 2.1. The final form is a closed-cell and thus water-proof when set. All mix types are lighter than water, yet strong enough to support the weight of an average sized male human on the area of a foot. Additionally, these foams attach to a variety of materials including wood, iron, and concrete, among others. Based on these characteristics, this material is suitable for use in disaster scenarios in real-time. Two projects have utilised a robotic PU foam depositing system for traversing obstacles.

1.3 Related Work

The first project of this type was proposed by Napp et al. [7]. The platform utilises a mechanised syringe to deposit small amounts of two part PU to create a ramp which allowed it to traverse an object larger than its original capability. This style of deposit system provides little mixing and thus very low expansion ratio of the foam, meaning a significant amount of material extrusion was needed to create said ramp. Also, continuous deposition was required if the syringe was to remain unblocked before using all of the material. For the ramp demo shown in this project multiple syringe cartridges and mixing devices were manually replaced on the system to allow continuous usage. One final remark on this system is that the single rigid nozzle deposit system and small expansion rate resulted in a very complex build requirement, which would be difficult to implement autonomously and was thus manually controlled by a human operator.

The second project of this type is that shown by Fujisawa et al. [5]. This platform utilised an aerosol depositing system on a gimbal, with both single part and two part PU tested. This system allowed much more flexible deposition than [7], and therefore an autonomous ramping system was possible upon detecting an object. However, the use of an aerosol depositing system gives little control over the material being deposited, as the mix ratio and outlet speed are determined with mechanical design and cannot be controlled by the system once setup. Also, the use of prepackaged aerosols brings into question how well this system could be scaled.

This project proposes an on board pumping and mixing system to drive the two part liquids of PU foam to reaction, thus giving complete control over the deposition.

2 Design

2.1 Deposit System

Peristaltic pumps are used to drive PU part one and two from their separate reservoirs to a mixing chamber. This chamber, shown in Fig. 1, ensures the two parts have been thoroughly mixed without increasing the turbulence to such an extent that the parts begin reacting. This mixing is necessary as multiple outlets are required and due to the viscous nature of the individual parts, the flows would otherwise develop separate channels with no mixing, as shown in figure Fig. 2. This balance between preventing channel development and averting PU reaction is achieved through a calculated design considering three primary parameters of the mixing chamber: inlet diameters, angle between PU inlets 1 and 2 and joint configuration between inlets/outlets. Inlet diameter primarily controls the flow velocity per pump rate. The angle between PU inlets effects how likely PU parts are to form separate channels. The joint style between inlets and outlets also has an effect on this. The final inlet diameters of $2mm$, angle between inlet 1 and 2 of 120° and central spherical joints connected between a straight cylinder allowed sufficient liquid velocities and contact momentum to ensure full dispersion without initiating reaction.

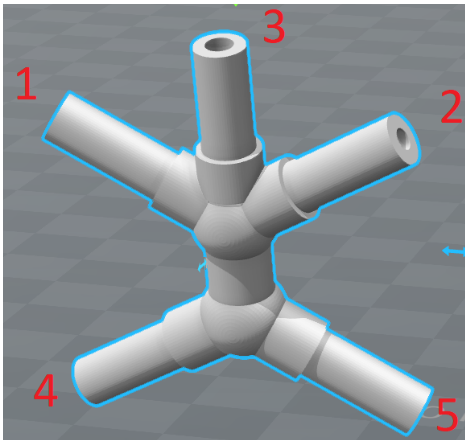

Fig. 1. Illustration of the mixing chamber designed. Labels 1 and 2 represent inlets for PU part 1 and 2 respectively. Label 3 represents the inlet for the solvent flush. Labels 4 and 5 highlight the outlets of the mix chamber, which will contain an even distribution of PU part 1 and 2 or the solvent depending on the stage.

Following the mix chamber the now combined PU is separated and passed through a static mixing nozzle (MA6.3-21S, Adhesive Dispensing Ltd.) before the outlet. A major drawback of previous systems were the blockages that occur between use, as after use residue will be left in the system and particularly the static mixing nozzles. For this a solvent (Isopropyl alcohol) is then autonomously flushed through the system to mitigate the reaction and eject any residue. This allows the system to be used multiple times without blockage or manual intervention. The whole process is illustrated in Fig. 3.

Driving the system with peristaltic pumps means that at any one time the amount of liquid being driven is equal to that in the tubing and mixing devices and is thus independent of the size of the reservoir from which it is being pulled.

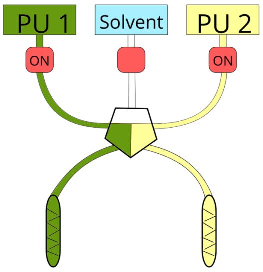

Fig. 2. Illustration of PU parts one and two not mixing, which occurs without a suitable mixing chamber.

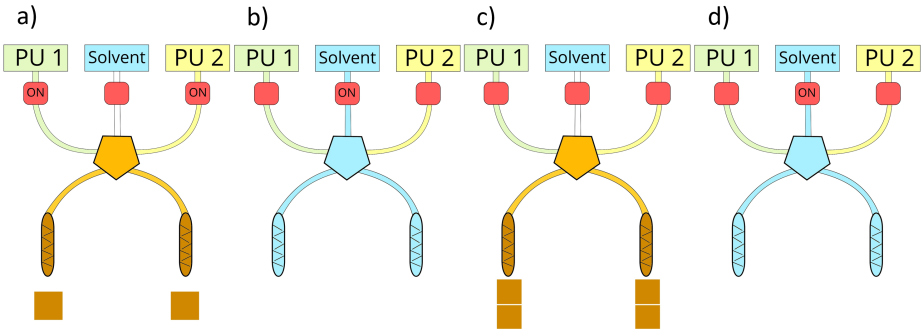

Fig. 3. Illustration of the stages of pumping PU part one and two to create PU foam and the solvent flush stages: a) Pumping of PU part one and two to create first batch of PU foam b) flush of solvent to ensure no blockages after use c)Pumping of PU part one and two to create second batch of PU foam d) flush of solvent. Peristaltic pumps are represented by red symbols, central pentagon represents the mixing chamber and crossed cylinder represent the static mixing nozzles.

Unlike syringe and aerosol driven designs [5, 7], this allows the system to be significantly scaled as the size of the reservoirs has no effect on the force needed to drive the depositing system.

Further, the system can control the rate of each pump independently. Altering the ratio of PU part one to PU part two alters the properties of the deposit as previously mentioned. For example, if the system required a harder deposit, it could autonomously increase the ratio of PU part one to the mix. Likewise, increasing the ratio of PU Part two would increase expansion ratio; this could be necessary if maximising the volumetric output was required. Additionally, increasing overall flow velocity increases the turbulence with which the chemicals are mixed, thus reducing the time taken to begin expansion. This has the potential to allow outputted material to be less fluid-like and more immediately sticky, where obvious applications would be to allow foam deposition on a vertical wall. However, making the deposit more liquid-like on exit allows the substance to be deposited into crevices and cracks which would not be possible for syringe or aerosol deposited systems. Increasing this rate of reaction makes the substance more likely to block the static-mixers and thus a maximum overall pump speed is set to prevent this.

Finally, the system allows two pumps to drive the liquids to two outlets, although it is possible to increase this number. The importance of this will be mentioned in Section 3.

2.2 Robotic Platform

As previously mentioned, this project puts forward a PU depositing system which has potential to be combined with any terrestrial robotic platform to extend its ability. For the purposes of testing, a simple low cost tracked rover was designed as follows.

Rover Design The rover used for the test is the two-tracked vehicle, with a track height of $100mm$ and a track length of $300mm$, shown in Fig. 4. The foam ratio been tested to easily support $0.42MPa$ (an $85kg$ human on a small section of the foot) whereas the rover in question has a pressure value of $0.02MPa$ ($15kg$ Rover on the total surface area of its tracks). The platform is driven by two large stepper motors (RB-Phi-266, Robotshop), which would allow a $50kg$ payload to be pulled along an even medium friction surface. The rover is driven by a central Arduino Mega 2560 board which controls the motor speeds via two Arduino Nanos and the pumping systems via another Arduino Mega 2560. A digital compass is connected to the central control board to feed orientation information back to the controller and positional information is estimated from motor steps. The PU Foam depositing system will be mounted on top of the rover with the two outlets positioned directly behind the tracks. As the rover moves, the foam will be deposited, forming two distinct extrusions which are aligned with the rovers tracks. Once the foam has expanded and solidified the rover can simply climb on said extrusions to increase or maintain altitude. When depositing foam in a straight line, controlling either deposit speed or rover speed allows the platform create ramp structures as will be seen in Section 4. This is an alternative to the complex depositing mechanism proposed in [5] and the complicated ramp structure required in [7].

2.3 Object Overcoming System

Basic ultrasonic distance sensors (HC-SR04) are utilised to determine the presence of obstacles or chasms in front of the vehicle. If an object is detected, a ramp construction procedure is initiated. Whereas, if a chasm is present, a void filling function is executed.

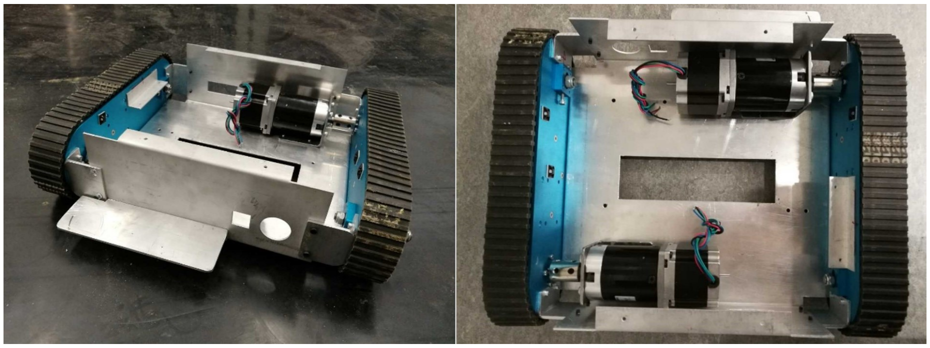

Fig. 4. Image of the rover platform.

Frontal Object Detection One sensor is placed at the front of the rover, at just above half of the rover track height. It was determined through testing that if an object is detected at this height or above, the rover will not be able to overcome it independently. As the rover cannot detect whether it is meeting an object perpendicularly, once the rover detects the object it will begin to move forward at a low motor torque to align the rover front face with the straight edge of an object. Once in contact with the object it will initiate the depositing protocol. A programmed deposit rate/time sequence is utilized that will produce a ramp thus allowing the rover to overcome an obstacle at half of the rover track height. Waiting times are also predetermined based on the amount of foam deposited from previously collected set times. If the obstacle is still detected after climbing on this deposit, then the same procedure will be repeated, but with increased ramp length. The rover can overcome minor over/under expansions for frontal obstacles that may occur. A flowchart of the autonomous response to objects and respective illustrations for the responses are shown in Fig. 5.

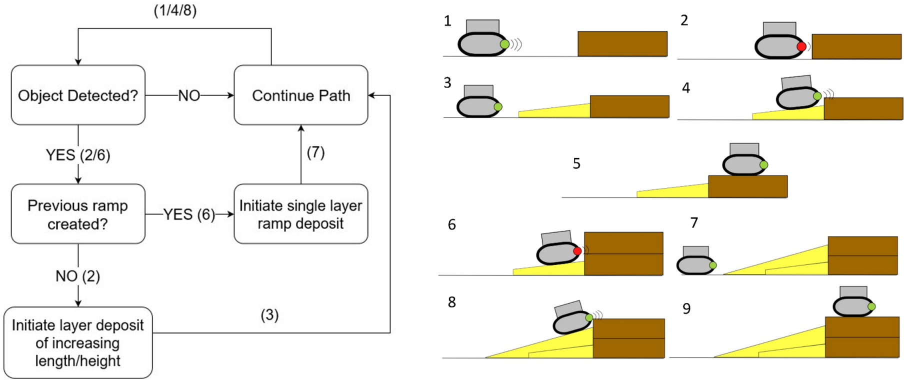

Fig. 5. Flowchart and illustration of the frontal object detection system.

Chasm Detection The other tested scenario is chasm detection, which considers detecting large gaps in the flooring preventing path following. Two sensors are placed on the undercarriage of the chassis, facing the ground. One is positioned near the front of the rover and the other in the center. The rover can overcome chasms of up to $100mm$ in length (one third of the total rover length) without falling into said gap. Therefore, if both forward and center undercarriage sensors detect a continuous gap, the rover will stop moving and initiate its void filling procedure. The rover will estimate the amount of deposit required from the depth measurements of the chasm, set values were taken heuristically. However, if it under deposited (for example if the foam expanded less than expected) then it would once again detect the chasm and repeat the filling procedure. Over-depositing typically leads to foam overflowing the chasm, but the amount is usually trivial for the rover to overcome. A flowchart of autonomous response to objects and respective illustration for the responses is shown in Fig. 6. Chasm detection is overridden when climbing a ramp produced by system 1.

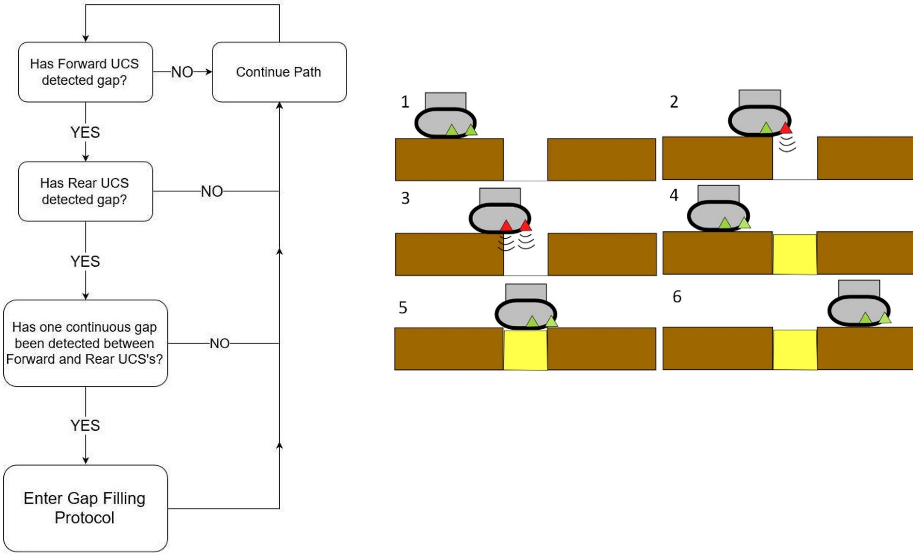

Fig. 6. Flowchart and illustration of the chasm detection system.

3 Results

Three experiments were carried out, with both detection systems being operational. The rover is given a straight line path which it is required to follow, if it detects any objects along this path it must work out how best to overcome them. All three experiments require the ability to: first, detect an obstacle that inhibits the rover's ability to follow the planned path, eject the PU foam correctly, flush the system to ensure no blockages occur, wait until the foam has cured and then overcome obstacle using the deposited foam. The first two experiments consider frontal obstacles and the third considers chasm detection. For all three tests the mix ratio of PU part one: part two was fixed at $1:1$ so that it can settle within 6 minutes, expand around 30× and have sufficient strength to support the rover weight. All three of these obstacles have been tested to ensure that the rover could not overcome them without using the PU depositing system, with the rover toppling/not able to grip onto the material for the frontal objects and getting stuck in the chasm. Total run time is taken from the moment the object is detected until the the time the object has been fully overcome (the entire rover is atop the object or passed the chasm).

3.1 Small Frontal Object Test

In this experiment a $60mm$ high block was placed along the rover's path, just over half of the $100mm$ rover track height. The rover detected the object, aligned itself and began the first layer ramp deposit procedure. It then waited for the foam to expand and solidify before using the deposit to continue its path; detecting no further obstacles along the way. The rover created the ramp, varying pump speed as it moved away at a constant speed with more material being deposited closer to the object as shown in Fig. 7. The total time to run this experiment was 6 minutes and 42 seconds.

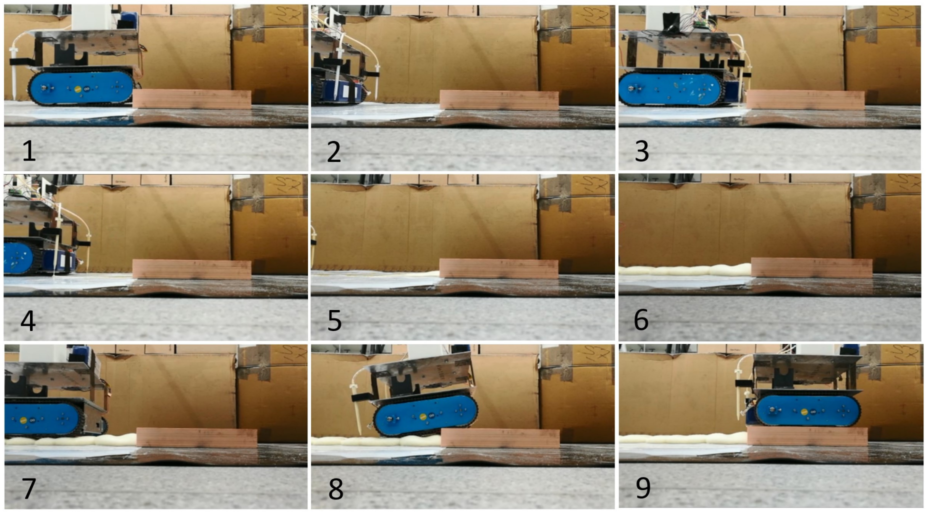

Fig. 7. Test one, the stages of the rover detecting a $60mm$ high block and depositing a ramp foam to overcome said block.

3.2 Large Frontal Object Test

In this experiment a 130mm high block was placed along the rover's path, 1.3× the rover track height. The rover detected the object and conducted the same first layer ramp deposit procedure as in test one. However, upon climbing the ramp, it detects the object once more. Knowing it has previously deposited a ramp, the rover initiates the ramping procedure but deposits foam for an increased duration/distance over the previously created ramps. The rover then waits for the second layer to cure and is able to overcome the object, as shown in Fig. 8. This success of this test proves that building large, multi-layered ramp structures is possible and that the system ensures no blockages occur between layers/uses. Total time for this experiment was 13 minutes and 42 seconds.

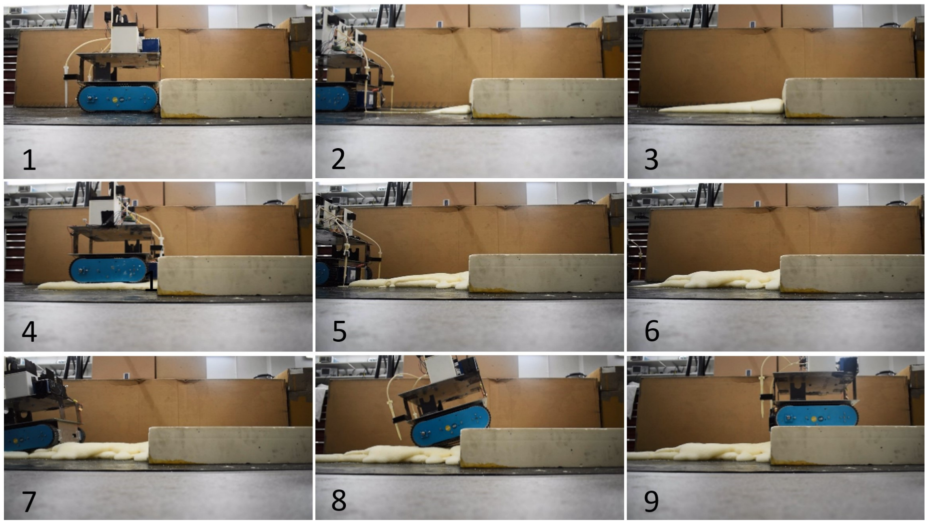

Fig. 8. Test two, the stages of the rover detecting a 130mm high block and depositing a ramp foam to overcome said block.

3.3 Chasm Test

In the final experiment a 160mm long chasm was placed along the rover's path, over half the 300mm rover tracks length. The chasm was 80mm deep and 400mm wide. The rover moves, first detecting a small gap with the frontal undercarriage sensor, the rover then moves more slowly to ensure it has sufficient time to either detect whether it is able or not to overcome the chasm without depositing material. This is performed by detecting a continuous gap between the frontal and rear undercarriage sensors. Once the rover detects that the chasm is too long and/or deep, it begins its the gap filling procedure. The rover estimates the amount of PU foam to be deposited using sensor depth measurements of the chasm, performs the deposit and then waits for this to expand and cure. The rover filled the chasm sufficiently and overcame the obstacle as shown in Fig. 9. Total time for this experiment time was 5 minutes and 60 seconds.

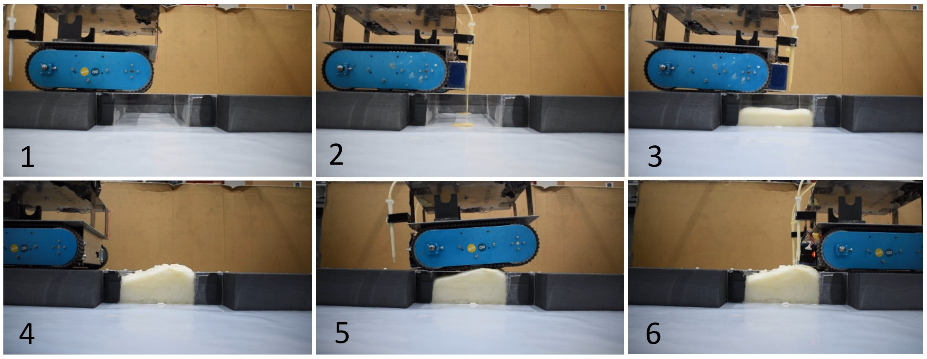

Fig. 9. Test three, the stages of the rover detecting a 160mm long chasm and depositing to fill said gap and overcome the obstacle.

3.4 Summary of experimental results

A summary of the experimental results is reported in Table 2, showing that the proposed PU foam depositing system enables the rover to overcome obstacles which were previously insurmountable. In all cases expansion ratio is between 29× and 32× the original parts, showing the robust control over the mixing process and, hence, the final mechanical properties of the foam.

Table 2. Summary of experimental results, where H=Height, D=Depth, L=Length and Vol=Volume

	Type	**Dimensions**	**Deposit Vol**	**PU used**	**Run Time**
Test One	Small Frontal	H: 60mm	2000cm^3	63cm^3	6mins42secs
Test Two	Large Frontal	H: 130mm	5000cm^3	170cm^3	13mins42secs
Test Three	Chasm	DxL: 100x200mm	4000cm^3	126cm^3	5mins60secs

4 Conclusion

In this paper an inexpensive and easy-to-use PU foam depositing system is proposed. The system is designed as an independent module for existing ground robot platforms to expand their capabilities. Thanks to its design, it can be utilised without complicated control algorithms to allow systems to autonomously overcome obstacles. This system, unlike others previously proposed, allows complete control over the deposited material. Specifically, it allows the PU foams expansion ratio and final compressive strength to be tuned autonomously according to the situational requirement. The flush system embedded allows the long term use of the module without blockage, a typical drawback for such systems. Initial tests show it provides significant extension to capabilities, with no drawbacks. Work presented in this paper is an early prototype and has not been extensively tested yet. In the near future we plan to extensively test the full capabilities of the system.

References

1. Alexander, D.A., Klein, S.: First responders after disasters: A review of stress reactions, at-risk, vulnerability, and resilience factors. Prehospital and Disaster Medicine **24**(2), 87–94 (2009). https://doi.org/10.1017/S1049023X00006610
2. Brunner, M., Brüggemann, B., Schulz, D.: Towards autonomously traversing complex obstacles with mobile robots with adjustable chassis (05 2012). https://doi.org/10.1109/CarpathianCC.2012.6228617
3. Bruzzone, L., Quaglia, G.: Review article: locomotion systems for ground mobile robots in unstructured environments. Mechanical Sciences **3**, 49–62 (07 2012). https://doi.org/10.5194/ms-3-49-2012
4. for Research on Epidemiology of Distasters (CRED), T.C., for Disaster Risk Reduction, T.U.N.O.: The human cost of weather related disasters 1995-2015 (2016), https://www.preventionweb.net/files/46796_cop21weatherdisastersreport2015.pdf
5. Fujisawa, R., Nagaya, N., Okazaki, S., Sato, R., Ikemoto, Y., Dobata, S.: Active modification of the environment by a robot with construction abilities. ROBOMECH Journal **2**(1), 9 (Apr 2015). https://doi.org/10.1186/s40648-015-0030-2
6. Murphy, R.R., Tadokoro, S., Nardi, D., Jacoff, A., Fiorini, P., Choset, H., Erkmen, A.M.: Search and Rescue Robotics, pp. 1151–1173. Springer Berlin Heidelberg, Berlin, Heidelberg (2008). https://doi.org/10.1007/978-3-540-30301-5_51
7. Napp, N., Rappoli, O.R., Wu, J.M., Nagpal, R.: Materials and mechanisms for amorphous robotic construction. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems. pp. 4879–4885 (Oct 2012). https://doi.org/10.1109/IROS.2012.6385718