A Robust Polyurethane Depositing System for Deployment on Disaster Scenario Robotics

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Abstract*—Robotic platforms have been widely recognised as potential tools for mitigating the aftermath of natural catastrophes. However, their ineffectiveness in traversing highly unstable and irregular terrains is a key bottleneck in their deployment and usage in real world scenarios. In this work, a Polyurethane Foam depositing system is proposed to allow ground vehicles to overcome obstacles and navigate on challenging substrates. The proposed system is designed as in independent modular mechanism that can be attached to various robotic platforms to enable material deposition and thus to increase their ability in overcoming obstacles. The materials used are inexpensive and their properties can be tuned on board by a simple control system, allowing the device to vary its output type according to situational requirements. Four different deposit types have been characterized, with expansion ratios varying from $20\times$ to $33\times$, compressive strengths from $0.16MPa$ to $2MPa$, and full expansion and set times below 6 minutes, allowing application in real-time. The system has been fitted to a tracked rover equipped with some basic sensors to allow autonomous responses when faced with obstacles. The system allows successful traversing of previously insurmountable obstacles such as large frontal 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; Overcoming Obstacles; Disaster Scenario.

I. INTRODUCTION

A natural catastrophe is an unexpected event caused by nature, which results in a great deal of suffering, damage and death. These include but are not limited to events such as, tornadoes, hurricanes, earthquakes, etc. According to a U.N. report [1], since 1995 over $600,000$ people have been killed, $4.1billion$ injured or left homeless and $\$2trillion$ in economic damages have been caused by such natural catastrophes. When natural disasters strike, the primary concern is human life and therefore it is critical to reach the victims and the survivors as soon as possible. People left stranded in the wake of these events are often stuck for days without food, water or medicines. They find themselves cut off from all support, typically due to collapsed infrastructure, making it impossible for teams to easily and safely reach them. This results in first responders being some of the most at risk during any relief efforts [2], often entering highly unstable areas with little knowledge of the interiors.

TABLE I. SYNTHETIC COMPARISON OF LOCOMOTION SYSTEM FEATURES, TAKEN FROM [8]. LeW = LEGGED WHEELED, LeT = LEGGED TRACKED, WT = WHEELED TRACKED, L=LOW, M=MEDIUM and H=HIGH

	W	**T**	**Leg**	**LeW**	**LeT**	**WT**
maximum speed	H	M/H	L	M/H	M	M/H
obstacle crossing	L	M/H	H	M/H	H	M
step climbing	L	M	H	H	H	M
slope climbing	L/M	H	M/H	M/H	H	M/H
soft terrain	L	H	L/M	L/M	M/H	H
uneven terrain	L	M/H	H	H	H	M/H
energy efficiency	H	M	L	M/H	M	M/H
system complexity	L	L	H	M/H	M/H	L/M

It is widely acknowledged that robotic platforms will play a key role in mitigating the after effects of such disasters. Major progress has been made in the developments of aerial, terrestrial and maritime robotic platforms specifically designed for use for disaster relief, search and rescue and salvage operations [3]. This is because robots can be deployed quickly in areas deemed too hazardous for human operation. Terrestrial platform specifically can be used to collect interior data, deliver supplies and support first responders. Many projects have been developed in recent years to achieve some of these functions, see for example [4]–[6]. However, when taking ground based platforms from the even surface of a lab to the unpredictable and often unstable terrain expected in disaster zone environments, they typically encounter major difficulties.

Numerous robotic architectures have been developed for the very purpose of overcoming rough terrain. Current approaches can be classified into roughly five categories according to [7]: single-tracked, multi-tracked, wheeled, quadruped-platforms (or biologically inspired systems) and humanoid. Each of these unique solutions can perform well in particular conditions, but there is no one of these categories that performs exceptionally in every circumstance. As a result of this, more focus has been recently put on the development of hybrid platforms to maximise the advantages of multiple architectures. However, such systems are expensive and their added benefits often limited. A comparison of tracked, wheeled, humanoid and their respective hybrids was performed in [8] and is reported in Table I. This overlooks quadruped and biologically inspired platforms as these represent a very diverse array of systems which are difficult to generalise. Table I shows that no architecture nor hybrid system can tackle all of the considered environments, therefore development of one particular locomotion style will not result in a system that is the most apt in all scenarios. Due to this, material deposition systems have been suggested as methods for augmenting robotic platforms to increase their ability of navigating uneven terrain.

In this paper, a novel Polyurethane (PU) Foam deposition system is proposed to increase a robotic platforms ability to traverse uneven terrains and overcome obstacles. The paper is structured as follows. In Section II, an overview of Polyurethane foam and the related works are given. In Section III, a brief description of the design for the depositing module, a characterisation of the deposited material and the integration with a tracked rover is reported. Section IV contains an illustration of the experimental setup used to test the effectiveness of the depositing systems, whereas the results obtained in these experiments are discussed in Section V. Finally, some final remarks and suggestions for further work are reported in Section VI.

II. BACKGROUND

A. Polyurethane Foam

Polyurethane Foam (PU) is a synthetic resin in which the polymer units are linked by urethane groups; when combining the two part constituents, the mix quickly expands and then sets rigid. The ratio between these two parts alters the final properties of the PU foam and therefore maximum values for such properties are the best way to characterise the material. Two key material characteristics for the purpose of this paper are:

- Compressive strengths - over $2MPa$ are possible, which can easily support the weight of a human standing thereon.
- Expansion ratios - over $30\times$ the original volume, meaning $25dm^3$ of final structure foam can be generated from $840cm^3$ of the two part liquid constituents [9].

The final properties depend largely on two factors: the mix ratio and the mix style. Therefore, different mixing mechanisms, such as manual stirring, syringe pumping and aerosol deposition, will result in very different final material properties. The importance of this will be further discussed in Section II-B. The final material form is a closed-cell and thus, water-proof foam when set and all mix types are lighter than water, yet strong enough to support the weight of a human. Additionally, these foams attach to a variety of materials including wood, iron, and concrete, among others. Based on these characteristics, this material is deemed suitable for use in disaster scenarios in real-time.

B. Related Work

Two projects have utilised a robotic PU foam depositing system for traversing obstacles. The first platform was proposed in [10] and utilised a motorised syringe prefilled with the two parts of PU. As the syringe is actuated, the two parts are driven through a series of static mixing chambers to increase turbulence and initiate reaction. This allows the system to deposit small amounts of PU foam to create a ramp which allowed it to traverse an object larger than its original capability. There are several major drawbacks of this system. Firstly, the style of deposition provides little mixing and thus very low expansion ratio of the foam, meaning a significant amount of material extrusion was needed to create the desired ramps. This low expansion ratio, coupled with the single rigid nozzle deposit system, resulted in a very complex build requirement, which would be difficult to implement autonomously and was thus manually controlled by a human operator. Further, 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.

An alternative approach was proposed in [9], where a robotic platform utilised an aerosol depositing system mounted on a gimbal, with both single part and two part PU tested. The two part PU resulted in much more effective outputs and a more flexible deposition than [10], and therefore an autonomous ramping system was possible upon detecting an object. However, the use of aerosol depositing system gives little control over the material being deposited, as the mix ratio and outlet speed are determined with the systematic design and cannot be controlled by the platform or even altered simply offline. Also, the use of prepackaged aerosols bring into questions how well this system could be scaled.

To overcome the drawbacks of existing platforms, this paper proposes an on board system to drive the two part liquids of PU foam to reaction. The proposed approach provides complete control over the deposition process and over the final material properties of the PU foam, thus eliminating the issues described above.

III. DESIGN

A. PU Foam Deposit System

The proposed PU foam deposit device is illustrated in Figure 1. Separate reservoirs are used to contain the required components: PU part one, PU part two. Pumps are used to drive PU parts one and two to an external mixing chamber. This chamber ensures the two parts are fully diffused without increasing turbulence to induce reaction. This is a necessary step when multiple outlets are required as in the platform described in this paper, otherwise the flows would not mix and develop into separate channels due to the viscous nature of the individual parts, see Figure 2. The now combined PU is separated toward two different static mixers acting as depositing nozzles.

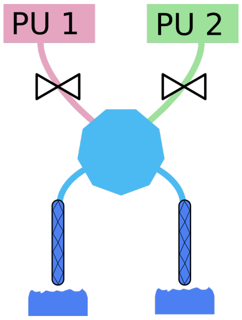

Figure 1. Schematic representation of the PU depositing device: PU part 1 and PU part 2 reservoirs are connected to a mixing chamber (light cyan octagon) via pumps (represented by white double triangles). The resultant mixture is then fed to static mixers (dark blue cylinders) that act as nozzles for depositing PU foam.

The proposed design results in a number of benefits when compared to systems available in the literature:

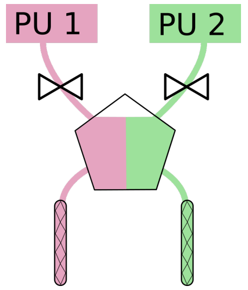

Figure 2. Illustration of PU parts one and two not mixing, which occurs without a suitable mixing chamber.

1) Basing the system around pumping mechanisms results in a fixed amount of liquid being driven at any one time. The amount of liquid being actuated is independent of the reservoir size from which it is being drawn. This, unlike syringe and aerosol driven designs [9], [10], allows significant scaling of reservoirs with no system alteration.
2) The system can use pumps to independently control the flow rate of each PU part. This allows complete control over the mix ratio and therefore the final mechanical properties of the deposited PU foam. For example, increasing the ratio of PU part two would increase expansion ratio; this could be used to maximise volumetric output if material was low. Conversely, if the system required a harder deposit, it could autonomously increase the ratio of PU part one to the mix.
3) Flow rate control allows control of fluid turbulence within the mixing devices. 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 vertical walls. 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.
4) 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 III-C.

B. Foam Characterisation

To demonstrate the control ability on the final material properties of the PU foam, four different PU foam types have been characterised according to: mix ratio, expansion ratio, initial compressive strength, final compressive strength, rise time and set time. Higher compressive strengths and expansion ratios are possible from this deposition system. However, mixes that result in higher expansion ratios, for example, result in compressive strengths that are too low to be considered useful for the envisaged applications, and vice versa.

PU foam is a high ductility material, hence it tends to experience large shape deformation instead of exhibiting brittle cracking behaviour under load. Therefore, two non standard definitions of compressive strength are used: initial compressive strength and final compressive strength. The former is defined as the pressure applied before permanent plastic deformation occurs, whereas the latter is defined as the pressure at which the height of the deposit is reduced by 70%. Beyond this value the deposit is considered to have failed. Controlled compression tests were conducted on an extracted cubic test sample from a free rise foam deposit. Force and compression/tension were measured with a material testing machine (Instron 3345) loading the specimens at a rate of $2mm/min$.

Set time is measured from initial deposition until the foam has fully solidified, and is calculated by removing multiple samples at set times and recording their compressive strength. Full set time is considered the point at which compressive strength no longer increases with increased reaction time.

Whilst absolute values of the properties have been measured and are of importance per se, the relative differences are the primary quantities of interest, as they demonstrate the capability of the proposed system to deliver enhanced control characteristics. A summary of properties of the deposited foams are reported in Table II, where each foam is defined by the mix ratio of part one to part two. Such table shows, for example, that the proposed device can create PU foams with compressive strengths ranging from $0.56MPa$ to $2MPa$.

C. Robotic Platform

The modular design proposed for the depositing system allows easy deployment on already existing robotic platforms, enabling their increased range of operation. For the purposes of testing, the simple low cost ground rover shown in Figure 3 was used. This platform is a two-tracked vehicle with a track height of $100mm$ and a track length of $300mm$. The maximum pressure exerted by the rover on the terrain is about $0.02MPa$ ($15kg$ rover on the total surface area of its tracks), therefore the PU foam can easily sustain the weight of the whole platform. The rover is driven by two large stepper motors (RB-Phi-266, Robotshop) controlled by a central Arduino Mega 2560 board which actuates the motor speeds via two Arduino Nano boards 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 based on encoder information from the motors. The PU Foam depositing system was 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 to create ramp structures as will be demonstrated in Section IV. This is an efficent approach compared to the complex depositing mechanism proposed in [9] and to the complicated ramp structure required in [10].

IV. EXPERIMENTAL SETUP

Two main simulated scenarios are designed to demonstrate the effectiveness of the proposed PU foam depositing system in allowing ground vehicles to navigate in a disaster scenario: obstacle climbing and chasm traversing. To this end, the

TABLE II. CHARACTERISATION OF FOUR TYPES OF PU FOAM DEPOSITION.

	Low Density	**Medium-Low Density**	**Medium-High Density**	**High Density**
Mix Ratio (one:two)	1 : 0.74	1 : 1	1 : 1.4	1 : 1.6
Expansion Ratio	33×	29×	25×	20×
Initial Compressive Strength	$0.16MPa$	$0.25MPa$	$0.41MPa$	$0.76MPa$
Final Compressive Strength	$0.56MPa$	$0.74MPa$	$1.37MPa$	$2MPa$
Rise Time	37 seconds	46 seconds	52 seconds	55 seconds
Set Time	$210 - 270$ seconds	$240 - 300$ seconds	$270 - 340$ seconds	$310 - 380$ seconds

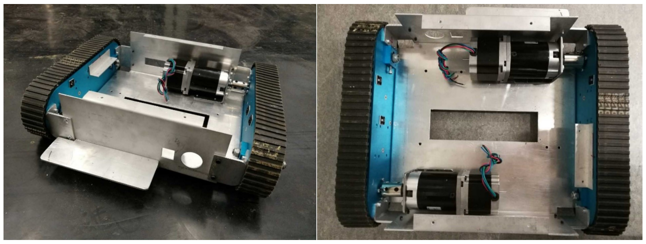

Figure 3. Images of the rover platform used for testing.

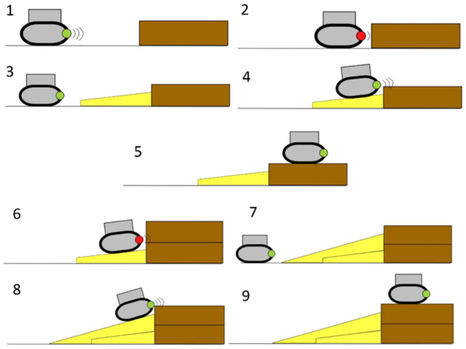

Figure 4. Illustration of the frontal obstacle detection system and ramp building process. Panels 1-5 show process used when a single ramp is enough to allow the robot to climb on the obstacle, whereas panels 6-9 show the procedure used to build higher ramps by depositing several PU layers on top of each other until sufficient height is reached.

robotic platform described in Section III-C was fitted with ultrasonic distance sensors (HC-SR04) pointing in the direction of travel and toward the ground to detect obstacles and/or chasms. If the sensors detect a scenario that would prevent the ground vehicle from proceeding on the planned path, a PU foam deposition protocol is initiated.

A. *Frontal Obstacle Detection and Climbing*

Frontal obstacles are defined as objects that are placed on the rover planned path and are too high to be overcome by the vehicle itself. Through testing, it was determined that the rover cannot overcome obstacles that are above half the rover track height. The frontal ultrasound sensor was then placed at this height and, once an obstacle is detected, the rover initiates a ramp depositing procedure in order to climb onto the obstacle. In particular, following detection of an obstacle, the rover will begin to move forward at a low motor torque to align the rover front face with the straight edge of an object upon contact. The ramp building protocol, schematically represented in Figure 4 is then initiated, giving rise to the creation of a ramp that the rover can use to climb onto the obstacle.

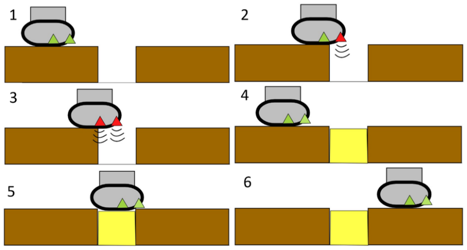

Figure 5. Illustration of the chasm detection and filling system.

B. *Chasm Detection and Filling*

A chasm is defined as a gap in the floor that is long enough to prevent the rover from moving over it without falling in. Through testing it was determined that the rover can overcome chasms of up to $100mm$ (one third of the total length) without falling into said gap. Longer gaps would prevent the vehicle to move along the planned path. Two ultrasound sensors were then placed on the underside of the chassis, pointing to the ground. One sensor was positioned at the front of the undercarriage and another one was placed at one third of the length from the front, in other words $100mm$ behind. These two sensors are necessary as some gaps in the floor, of less than $100mm$ in length, can be overcome by the rover without need for material deposition. However, if both undercarriage sensors detect a continuous gap, the rover will stop moving and initiate a void filling procedure. At first, the rover uses depth measurements of the chasm to estimate the amount of deposit required. However, if it is 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 extra amount is usually trivial for the rover to overcome. An illustration of the autonomous response to chasms is shown in Figure 5. Of course, chasm detection is overridden when climbing a ramp produced by the system described in Section IV-A.

V. RESULTS

Three experiments were carried out with both detection systems being operational. In all experiments, the rover is instructed to move in a straight line and the detection systems will determine whether or not they should activate the PU foam deposit procedures in order for the rover to continue to navigate along its planned path. All experiments require the on-board autonomous decision system to:

1) Identify an obstacle or a chasm preventing forward movement.

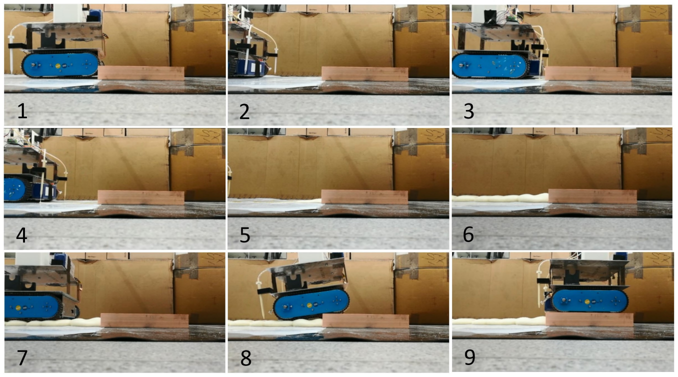

Figure 6. Small obstacle test: the stages of the rover detecting a $60mm$ high block and depositing a foam ramp to climb onto the obstacle.

2) Deposit the PU foam to overcome said obstacle according to the procedures described in Section IV.
3) Wait an appropriate amount of time for the PU foam to set.
4) Climb onto the obstacle or move over the filled chasm using the deposited PU foam.

The mix ratio of PU Part one:Part two was fixed at $1 : 1$ (Medium-Low Density foam) for all three tests. The first two experiments consider frontal obstacles and the third considers chasm detection. In all the scenarios the vehicle could not navigate along the planned path without the aid of the PU foam depositing system. For the frontal obstacles, the rover would either topple or slip when trying to climb on the objects. In the case of the chasm, the rover would simply fall into it.

A. *Small Frontal Obstacle Test*

The first experiment considered a $60mm$ high block - 60% of the $100mm$ rover height - blocking the rovers path. As can be seen from Figure 6, the rover detected the object using the embedded ultrasound sensor and initiated its ramp creation procedure. The system created a sloped ramp by controlling flow rate according to the distance from the obstacle. The system then waited for the foam to expand and solidify before using the deposit to climb onto the obstacle. The total time to run this experiment was 6 minutes and 42 seconds.

B. *Large Frontal Obstacle Test*

In the second experiment, a $130mm$ high block - 130% times the rover height - was placed along the planned path. Upon successfully detecting the object, the rover initiated the ramp building procedure as in the previous scenario. However, upon climbing the ramp, it detects the object again. The system, knowing it has previously created a ramp, then starts a different ramp creation procedure aimed at depositing a second layer that is longer than the first ramp, as shown in Figure 7. After curing, the platform used the two-layer ramp to climb onto the obstacle. Total time for this experiment was 13 minutes and 42 seconds.

C. *Chasm Test*

In the final experiment, a $160mm$ long chasm was placed along the rovers path - over half the $300mm$ rover tracks length. The chasm was $80mm$ deep and $400mm$ wide. Once the forward undercarriage sensor detected a gap, the rover reduced its speed to ensure it had sufficient time to detect a potential chasm. Once the second sensor detected the same continuous gap, the decision logic inferred that no flooring is present between the two sensors, hence the chasm filling procedure was initiated. The material depositing system estimated the amount of material to be deposited from the knowledge of the depth of the chasm (measured by the undercarriage sensors), performed the deposit and then waited for this to expand and solidify. The rover successfully filled the chasm and traversed the gap as shown in Figure 8. Total time for this experiment time was 5 minutes and 50 seconds.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, an inexpensive and easy-to-use PU foam depositing system is proposed. The system is designed as an independent module that can easily be integrated into existing robotic platforms to broaden their navigation capabilities on uneven terrains. This system does not require any complicated control systems, but it allows significant obstacles and chasms to be overcome. The primary benefit of this system when compared with others available in the literature is the complete control over the mix ratio and the deposit process. This allows control over the mechanical properties of the deposited material, allowing the PU foams expansion ratio and final compressive strength to be altered autonomously according to the situational requirement. The proposed device mitigates the main obstacle for using ground robots in disaster scenarios: traversing uneven terrain. Future developments may include the development of intelligent algorithms for optimising mix ratios according to the situation detected by sensors, scaling of system for increased range of applications, and collaborative robotics to tackle more complex and large scale efforts.

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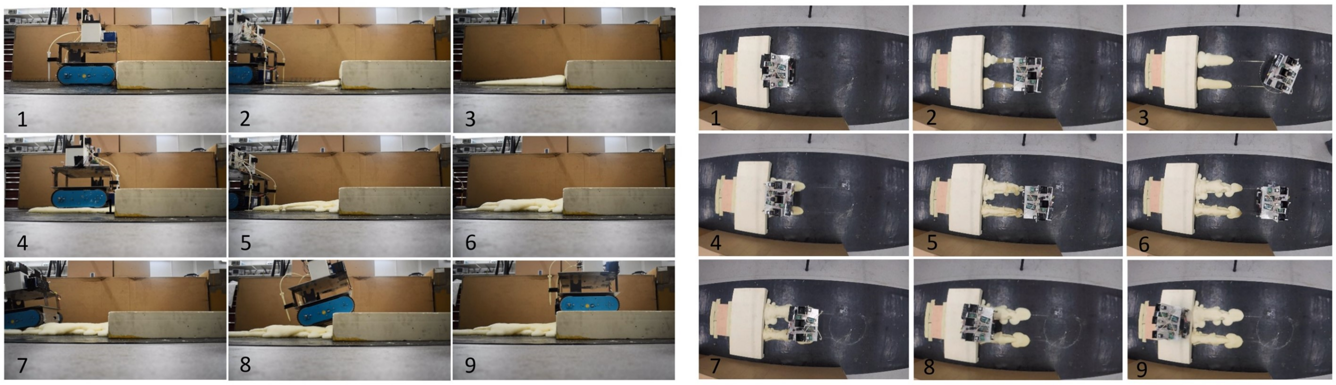

Figure 7. Large obstacle test: the stages of the rover detecting a $130mm$ high block and depositing a two-layer foam ramp to climb onto the obstacle. Left: side view, Right: top view.

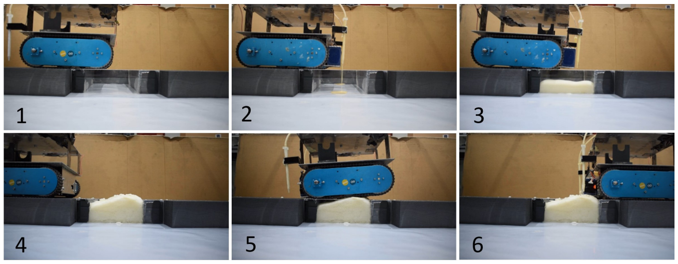

Figure 8. Chasm test: the stages of the rover detecting a $160mm$ long chasm and depositing PU foam to fill the gap and traverse the chasm.

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