D.R.O.P. The Durable Reconnaissance and Observation Platform

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***Abstract*— The Durable Reconnaissance and Observation Platform (DROP) is a prototype robotic platform with the ability to climb concrete surfaces up to 85° at a rate of 25cm/s, make rapid horizontal to vertical transitions, carry an audio/visual reconnaissance payload, and survive impacts from 3 meters. DROP is manufactured using a combination of selective laser sintering (SLS) and shape deposition manufacturing (SDM) techniques. The platform uses a two-wheel, two-motor design that delivers high mobility with low complexity. DROP extends microspine climbing technology from linear to rotary applications, providing improved transition ability, increased speeds, and simpler body mechanics while maintaining microspines ability to opportunistically grip rough surfaces. Various aspects of prototype design and performance are discussed, including the climbing mechanism, body design, and impact survival.**

I. INTRODUCTION

Current remote presence needs of the U.S. Department of Defense and NASA are underserved by the state of the art in robotics. Generally, deployed platforms are large, have limited mobility on non-flat terrain, have limited portability, and lack stealth (i.e. Talon [1], Packbot [2]). Conversely, many research platforms have become so small that the limitations on range, terrain, and payload reduce their utility in the field (i.e. DASH [3], Waalbot [4], MEDIC [5], etc.). The Durable Reconnaissance and Observation Platform (DROP), shown in Figure 1, seeks to fill a niche between these paradigms as a platform that can carry a 100 gram reconnaissance payload (2.4 GHz video camera and microphone) and has a functional range (>100m), but is light enough to be crash-proof. RECONRobotics‘ Scout platform [6], [7] is one of the few robots that combines these capabilities. DROP provides enhanced mobility over Scout with the ability to mount curbs, climb walls, and perch on rooftops.

DROP also extends the state of the art for climbing robots by demonstrating impact survival and rapid horizontal to vertical transitions. Multiple robots have demonstrated vertical climbing using a variety of attachment technologies generally suited to specific climbing surfaces [8], including magnets [9], [10], [11], [12], [13], [14], [15], [16], suction [17], [18], vortex [19], [20], pressure sensitive adhesives [21], [22], electrostatic adhesives [23], gecko-like adhesives [24], [25], [26], [27], and single claws [28]. On rough surfaces like brick, stucco, and concrete, almost all of these methods fail to achieve sufficient adhesion for mobility. Microspines, however, have been used successfully on these materials by the RiSE robot [29], Spinybot II [30], and perching airplanes [31], [32], as well as by human climbers [33]. All of these applications use microspines in a linear motion, engaging the sharp hooks by dragging the spines tangent to the climbing surface. This leads to legged architectures with multiple degrees of freedom and limitations on speed based on the inertial changes due to the cycling of legs back and forth. By overcoming the challenges of a rotary implementation of microspine technology, DROP is able to move at much higher speeds with a simple two-wheel architecture, and possesses superior maneuverability on flat ground. This architectural change also enabled the robot to transition from horizontal to vertical surfaces more rapidly and reliably than its legged cousin, RiSE [34], one of the few climbing robots able to perform such a maneuver at all.

Fig. 1. The Durable Reconnaissance and Observation Platform (DROP) weighs ~300 grams and is ~100 mm long. DROP is capable of climbing 85° rough surfaces at 25cm/s, move across flat ground at 45cm/s, and make rapid horizontal to vertical transitions. This is enabled by a new rotary implementation of microspine technology. DROP carries a wireless audio/visual payload (100 grams) that can relay reconnaissance information from rooftops and perches high on walls. DROP can survive impacts from heights greater than 3 meters.

Improving durability is important to increasing the reliability of any robot; in particular climbing robots that have the potential to see large impacts during unexpected detachments. One common method of improving durability is to increase platform robustness. This approach can be seen in robots such as iRobot‘s PackBot and SUGV which are designed to traverse a variety of horizontal surfaces with a high degree of reliability [2]. This high level of reliability has led to these platforms being employed by many organizations for defense operations. A significant trade off with this increased robustness often comes in the

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Fig. 2. Rotary Microspines use the the principles of independent suspensions and probaballistic attachment that were developed for linear microspines, but simplify the kinematics of the robotic implementation. Here, 4 microspine hooks are shown arrayed on a Rotary Microspine, each attached by a thin, stretchable, C-shaped flexure. Multiple holes in the frame allow arrays of Rotary Microspines to be configured at different angles with respect to neighboring Rotary Microspines.

form of large gains in mass. Therefore, this approach is not desirable for improving the durability of climbing robots, which are inherently sensitive to total mass. Other robots display improved durability by increasing shock absorption or by decreasing mass, which can greatly reduce forces on the robot during impacts. Examples of platforms which rely on shock absorption include RECONRobotics' Scout platforms [6]. These robots have also proven useful in defense and police applications because their small size and durable construction allows them to be easily implemented in a variety of ways. A quintessential example of a robot that uses mass reduction to improve durability is UC Berkley's DASH. DASH is a legged, crash-proof robot weighs only 16 grams that is capable of surviving falls at terminal velocity [3].

DROP incorporates facets of all of these platforms. The DROP project's main goal is to create a robot that is low-cost, lightweight, durable, and capable of high mobility, including vertical climbing and all horizontal/vertical transitions. DROP is built to carry an audio/visual payload to provide a remote presence for its operator, and is being developed for aerial deployment via UAV or ground deployment via UGV or human operator. Using shape deposition manufacturing (SDM), selective laser sintering (SLS), and rapid, iterative, prototyping techniques, a proof of concept platform was built with a new microspine climbing mechanism and an impact resistant body design. This teleoperated robot represents the first step towards fulfilling the DROP project goal.

II. DESIGN

A two-wheeled design was used to create the first DROP platform since it allowed the robot to be produced and assembled quickly and lowered the complexity and associated weight of the robot. This architecture has been successfully implemented in robots such as JPLs AXEL [35] and RECONRobotics' Scout, although it is not often implemented in climbing robots. The simplified, design-and-build quickly approach also freed researchers to concentrate on the development of the microspine climbing mechanism.

A. Climbing Mechanism

Inspired by climbing insects and spiders, microspine technology uses arrays of 10s to 1000s of independent sharp steel hooks to grip microscopic asperities (bumps, holes, and slopes) on rough surfaces [36], [37]. Microspines can attach to porous, often dusty surfaces such as stone, wood, and concrete where other attachment mechanisms fail. Microspines require no power to maintain grip, are compact, and lightweight. Therefore, they are a logical choice for a lightweight platform designed to operate in a wide range of natural and manmade environments. On DROP, microspines are incorporated in a completely new manner that allows climbing without complex mechanics or controls, allows for rapid ground travel, and easily transitions from horizontal to vertical surfaces.

All previous microspine applications have used a linear engagement and disengagement motion. DROP was developed around a rotary motion that uses a new circular configuration of microspines that provide continuous engagement with the climbing surface. Similar to other microspine climbing mechanisms, rotary microspines use a suspension feature that enables each microspine hook to engage the surface independent of adjacent hooks, and allows it to remain engaged through a large range of motion as the rotary microspine spins. Figure 2 shows the fourth iteration of the rotary microspine design. ~40 rotary microspines are arrayed at varying angles on the DROP prototype, producing secure engagement and making climbing possible.

The primary consideration when designing rotary microspines was the engagement angle of the microspine hook with respect to the climbing surface, denoted as theta in Figure 3. An engagement angle of between 30° and 45° is preferable to maximize the ratio of climbing force (F_c) to adhesion force (F_a) [28] . Because the motion of the rotary microspine results in a continually changing hook angle, the overall design of the climbing mechanism was greatly influenced by the need to constrain the hook engagement angle. Setting $\theta = 30^\circ$ and l_t and h such that the maximum rotation of the hook housing is limited to 15° created the desired range of hook angle of between 30° and 45° throughout the rotation of the rotary microspine. The rotation of the rotary microspine disengages the hook from the surface by applying a force through the main flexure that rotates the hook housing, causing a decrease in hook angle theta and eventual release.

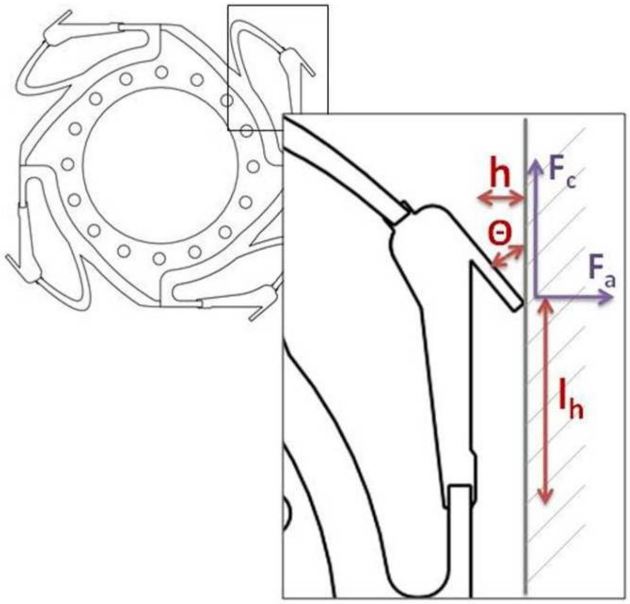

Fig. 3. Free Body Diagram of a Rotary Microspine. The Rotary Microspine was designed for a hook engagement angle of $\theta = 30^\circ$. As the rotary microspine spins, the hook will disengage naturally, being pulled away by the flexure.

The use of a two wheeled design, not often used in climbing robots, creates a unique set of criteria which needed to be accounted for in the body design (Figure 4). Two criteria needed to be met for climbing to occur:

$$F_{a,max} \geq F_r \tag{1}$$

$$F_c > F_{mg} \tag{2}$$

The torque exerted by the motors causes the tail of the robot to rotate into the surface being traversed. Without this reaction, F_r, the body of DROP would spin freely in place. During climbing, however, this reaction force has the potential to pitch the robot off the climbing surface. The length of the body, l_t, and the radius of the microspine sprocket, r, were adjusted to account for this and provide a balance of horizontal and vertical mobility.

Expanding F_r in Equation 1, Equation 3 displays the inverse relationship that exists between the maximum adhesion force generated by the microspine hook, $F_{a,max}$, and the body length, l_t.

$$F_{a,max} \geq ([F_{mg} * r + T]/l_t) \tag{3}$$

Increasing the body length, l_t, improved climbing by virtue of reducing the necessary adhesion force, but inversely impacted turning ability and ground travel. While the radius of the microspine sprocket has an effect on the reactions seen on the tail, F_r, it was more important in determining the climbing force produced by the microspine hook, F_c. Eq. 2 can be rewritten to show this relationship:

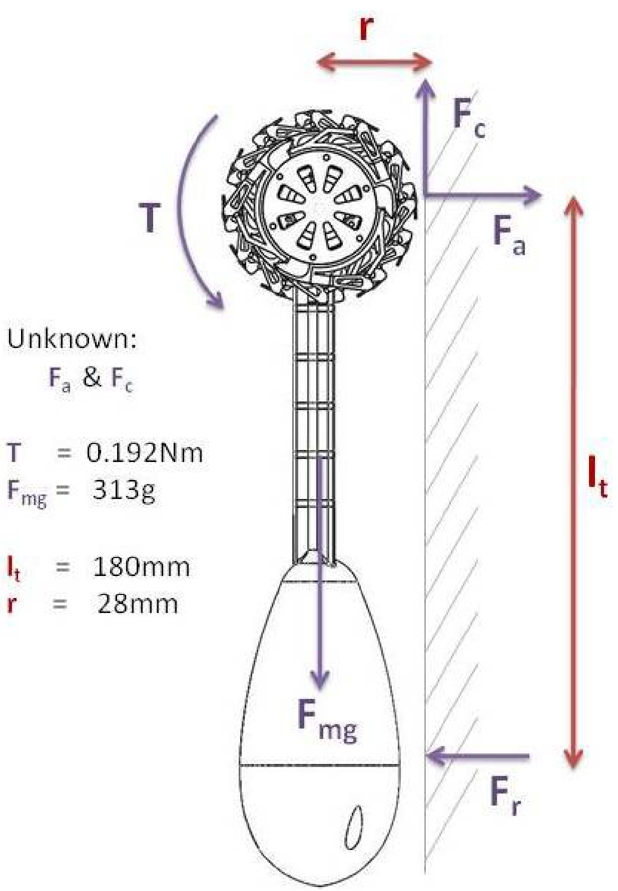

Fig. 4. Free Body Diagram of DROP. Using a wheeled configuration of microspines presents new challenges in body design. The tail length presents a design tradeoff between the induced pitchback moment that is produced at the hook and the maneuverability on flat ground and through transitions.

$$[T/r] > F_{mg} \tag{4}$$

Future iterations will largely address these design considerations of the body to improve performance by reducing the pitchback moment reflected to the spines during climbing.

Rotary microspines were designed to maximize the likelihood of hook engagement, transfer the load to the robot appropriately, and prevent tangling or fouling of the hook elements during repeated use. Flexure shape and stiffness were improved through empirical testing using groups of 5 or 10 rotary microspines on a vertical test apparatus with linear slides for repeatability. The side-by-side arrangement and angular variation of the rotary microspines were determined in a similar fashion. For initial prototyping, two materials were considered for the flexure segments, one of hardness Shore 20A and the second of hardness Shore 60A. Testing of several iterations of sprocket designs resulted in the selection of flexures of shore 60A hardness and the design shown in Figure 2. Using this rotary microspine design, several side-by-side arrangements were tested to reduce issues such as entanglement and twist. Entanglement was the tendency of hooks to extend and engage adjacent hooks, greatly hindering

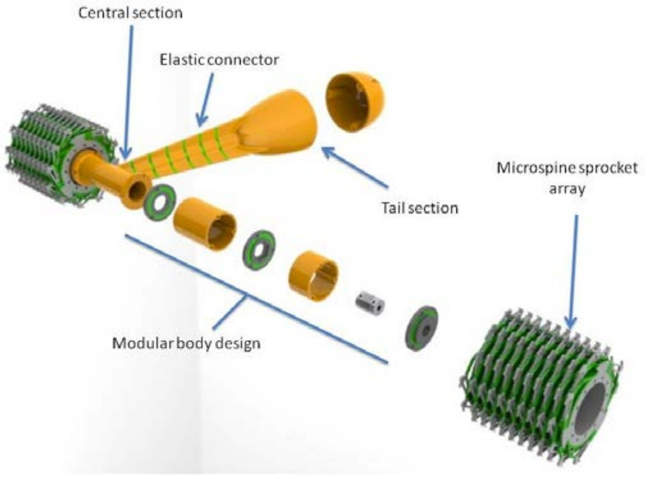

Fig. 5. The body of DROP was designed to be modular and durable. High impact resiliency plastic (via SLS) and flexible elastomeric material (via SDM) were used to create a durable body, with extra damping around critical electrical connections. Flexures were also inside the body to reduce the peak accelerations seen by the motors during impact.

the probability of engagement with the climbing surface. Twist was the tendency of the hook housing to rotate out of the plane of the sprocket. This effectively eliminated any possibility of engagement as the hook would often end up parallel to the surface instead of in the desired perpendicular orientation. These issues were resolved through the combination of an exaggerated support flexure, the C-shaped segment at the top of the hook housing in Figure 2, and by the inclusion of dividers between each sprocket to constrain the motion of the hook housing to the plane of the sprocket.

B. Body

The body of DROP merges structural elements necessary for vertical climbing with impact resistant features and compliance. The main sections of the body are radially symmetric and allow impacts to be absorbed similarly regardless of the orientation of DROP during impact. The body is constructed from materials that are lightweight and durable and features multi-material construction. The strategic use of impact dampening materials, such as polymers in the Shore 20A-60A hardness range, serves to reduce the impact forces seen by the motor coupler, electronic controls, and audio/video payload, those parts most susceptible to impact failure.

The body of DROP is constructed from a selective laser sintered (SLS) high-elongation polyamide-based material, which can be produced quickly, cheaply, and features high impact strength. The body is divided into two main components: a central section, which houses the motors, and a tail section which contains the batteries, RF receiver, and microprocessor unit, seen in Figure 5. The center and tail electronics are connected by the tail itself, which features alternating sections of SLS material and a polymer of Shore-60A hardness. These alternating sections of hard and soft material operate like the vertebrae in a spine, allowing the tail to bend and twist relative to the central section. Since they are not rigidly connected the two sections are capable of absorbing impacts independently and the tail aids in absorbing impacts via its capacity to deform. Future tail designs may include tendon-like cables that would provide anisotropic stiffness in different bending directions, and could be used to actuate the tail for certain behaviors.

C. Electronics

DROP‘s controls are simple and direct. Two motors provide sufficient torque for the robot to climb at a weight of up to 400g (the 300 g robot plus up to 100 g of payload). An ATmega328 microcontroller is used to control the motion of the robot, making it possible to accurately command the rotation of the rotary microspines depending on remote user or sensor input. A hybrid open-loop control architecture used one set of gains at low throttle for controlled climbing, and another set of gains at high throttle for high speed ground travel. Using this controller also makes it easy to expand the sensor and control features of DROP during future research. A 7.4V, 180mAh LiPo battery pack provides DROP with approximately 20 minutes of mission life. DROP can accommodate 720 mAh battery packs that provide more than 1 hour of operation, but this extended mission life is at the expense of climbing speed due to the increased weight. The current prototype uses a 2.4 GHz off the shelf nanny-cam as the audio/visual payload. This proof of concept payload streams information to a desktop computer in the laboratory independent of the operator, and is not intended to represent the state of the art in camera or microphone technology.

III. RESULTS

The current DROP prototype has the ability to transition from horizontal to 90° vertical surfaces, travel at a ground speed of 45cm/s, climb concrete faces up to 85° at 25 cm/s, and survive impacts from 3 meters. The platform can turn in place on flat ground and can travel at headings up to 20° off of vertical on walls. A related video submission shows these achievements.

Horizontal to vertical surface transitions were achieved with a high degree of repeatability, see Figure 6. These transitions were possible at a variety of speeds, including full throttle. Transitions from vertical to horizontal, however, were only partially successful with the current body design. The mass of the controls at the end of the tail in conjunction with the stiffness of the tail prevented DROP from moving its center of mass over the lip of the wall to transition onto the roof. A softer tail, lighter controls, or higher torque motors will address this issue.

The climb speed on an 85° inclined surface of 25cm/s is more than 5x that of RiSE (4cm/s) [29] and more than 10x that of Spinybot (2.3cm/s) [30]. The 45cm/s ground speed of DROP is also a rate unseen in other microspine climbing robots. DROP displayed high maneuverability on horizontal surfaces with the ability to turn in place (turning radius of 0) and overcome small obstacles with ease.

Preliminary impact testing was performed by driving DROP off of a one story rooftop. The platform survived these

Fig. 6. DROP makes reliable horizontal to 90° vertical surfaces in less than 2 second. A sequence of this transition onto a cinder block test wall is seen here, chronologically from left to right.

falls of 3 m, and was also thrown from the ground onto the roof to demonstrate one potential deployment strategy. From higher rooftops, DROP failed consistently with a crack to the unprotected edge of the plastic coupling between the motors and the rotary microspines. Redesigned couplers with additional protective damping material are currently in fabrication, and should improve impact resiliency.

IV. DISCUSSION

This paper introduced the first prototype of DROP, a small two-wheeled reconnaissance robot designed for fast traverse of both horizontal and vertical rough surfaces, and the corresponding transitions. DROP has several potential applications including use as a remote presence for disaster relief efforts, in combat scenarios for the military, and for commercial inspection of concrete structures like dams and buildings.. The ability to be transported easily and deployed rapidly makes this robot ideal for many situations where time and space are at a premium. With improved impact resistance, the ability to deploy DROP from the air would allow wide scale dispersal patterns that could generate 3d maps of urban environments, or perform extended perch and stare missions. Future versions of DROP may also be relevant for space exploration, serving as daughter payloads to larger, MSL-class rovers extending the types of terrain a mission could examine without jeopardizing the main rover.

DROP extends the state of the art in climbing robots by demonstrating rapid transitions from horizontal to vertical surfaces and improving climbing speeds on near-vertical inclines (85°). These transitions are an important part of creating a useable robot that has functionality in real world scenarios. Achieving near vertical climbing using a wheeled design has been accomplished in other robots (magnetic, adhesive); however, none of the robots using this design are capable of climbing concrete, brick, or stone surfaces. Future versions will address the issues in the interaction between the tail and rotary microspines that currently limits the climbing capability to 85°.

The combination of size and durability exhibited by DROP fills an underserved niche in reconnaissance robots. DROP, like RECONRobotics Scout, is able to operate over a useful range of >100 meters and is light enough to survive the impacts of being deployed by throwing or dropping. Being able to carry an audio/visual payload of ~100g on both horizontal and vertical surfaces and surviving modest impacts will allow future versions of DROP to collect high quality surveillance data from discreet perches on rooftops or high on walls, exceeding the performance of Scout, which cannot climb over curbs or maneuver on vertical surfaces.

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