D.R.O.P.

The Durable Reconnaissance and Observation Platform

Clifford McKenzie[1]
North Carolina State University, Raleigh, NC 27695

Aaron Parness[2]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Robots can provide a remote presence in areas that are either inaccessible or too dangerous for humans. However, robots are often limited by their ability to adapt to the terrain or resist environmental factors. The Durable Reconnaissance and Observation Platform (DROP) is a lightweight robot that addresses these challenges with the capability to survive falls from significant heights, carry a useable payload, and traverse a variety of surfaces, including climbing vertical surfaces like wood, stone, and concrete. DROP is manufactured using a combination of rapid prototyping and shape deposition manufacturing. It uses microspine technology to create a new wheel-like design for vertical climbing. To date, DROP has successfully engaged several vertical surfaces, hanging statically without assistance, and traversed horizontal surfaces at approximately 30 cm/s. Unassisted vertical climbing is capable on surfaces up to 85^{o} at a rate of approximately 25cm*s^{-1}. DROP can also survive falls from up to 3 meters and has the ability to be thrown off of and onto rooftops. Future efforts will focus on improving the microspine wheels, selecting more resilient materials, customizing the controls, and performing more rigorous and quantifiable testing.

I. Introduction

In situations where robots are used due to the inherent danger to humans, such as space exploration, disaster relief, and wartime maneuvers, the conditions under which they must operate are rarely defined. Having a robot with a high degree of adaptability becomes crucial in these situations. The adaptability that comes from high mobility and high durability greatly increases the potential uses of a robot in scenarios like those above. For example, robots that are too cumbersome and lack durability can't easily access high value areas where information is often of great value but also equally difficult to acquire. In contrast, those that are small and durable typically aren't as mobile as their larger counterparts and rarely carry a useful payload, making them of limited use for gathering information. Incorporating mobility and durability into a single platform that is highly portable and capable of carrying a useable payload is difficult and has yet to be fully achieved. The Durable Reconnaissance and Observation Platform (DROP) will address this need by creating a lightweight robot with the capability to survive falls from significant heights, carry an audio/video surveillance package, and traverse a variety of surfaces, including climbing vertical surfaces like wood, stone, and concrete.

[1]Intern, Mobility and Robotic Systems - JPL, North Carolina State University, Raleigh, NC
[2]Member of Technical Staff, Mobility and Robotic Systems, JPL, 4800 Oak Grove Drive M/S 82-105

While no one platform accomplishes the goals of DROP several display characteristics DROP seeks to incorporate. Although several existing platforms display mobility in the vertical environment, such as SpinyBot, RiSE, and WaalBot, they are typically not durable enough to survive falls from any significant height [1,2]. Another common shortcoming of existing climbing designs, particularly those that use microspine technology, is their inability to make efficient transitions between ground travel and climbing and vice versa. These issues greatly limit the usefulness of these robots for real-world applications where conditions are unpredictable and a lack of durability lends itself to questionable reliability. 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 [3]. Unfortunately, increased robustness is usually accompanied by gains in mass and is therefore not a desirable approach from climbing robots. Others display improved durability by increasing shock absorption, examples of this include Throwbot and Scout, or by decreasing weight, which can greatly reduce forces on the robot during impact [4]. DASH is the best example of improved durability with weight reduction; the legged, crash-proof robot weighs only 16 grams that is capable of surviving falls at terminal velocity [5] (Fig 1).

DROP incorporates facets of all these platforms. The goal of DROP is to create a robot that is lightweight, durable, and capable of climbing a variety of vertical faces. Adding to its usefulness, the platform will also be able to make transitions from horizontal to vertical surfaces, and vice versa, and in time will be developed for aerial deployment via UAV. Using shape deposition manufacturing (SDM) and rapid prototyping, a new microspine climbing mechanism and simple body design are used to construct a robot that can accomplish these goals.

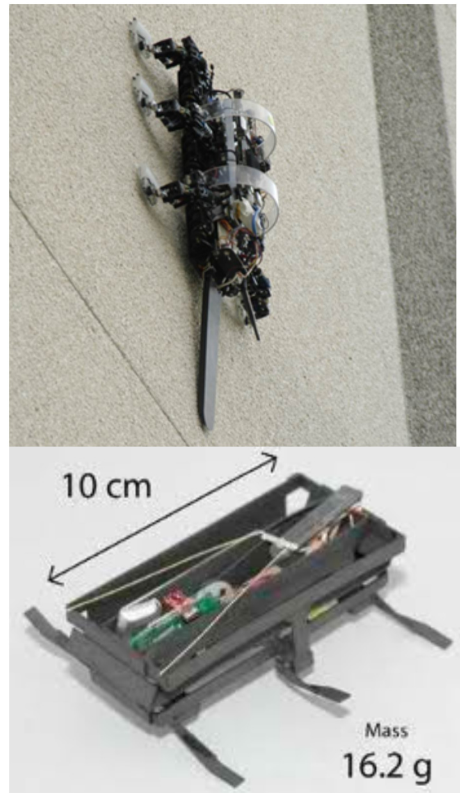

Fig 1. RiSE robot (top) and DASH (bottom) display several of the desirable characteristics DROP seeks to incorporate. RiSE is uses microspine climbing technology to scale vertical surfaces and DASH displays reduced weight and high durability.

Climbing with Microspines

Vacuums/suction, wet and dry adhesives, magnets, gripping mechanisms, and microspines have all been used for robotic climbing [6,7]. Typically, each of these technologies is intended for a specific climbing media and often works poorly or not at all on surfaces which it was not designed for. Of these technologies none is more suited to natural, unstructured terrain than microspines. Developed from mechanisms found in some climbing insects and spiders, microspines are a desirable method of attaching to porous, often dusty surfaces such as stone, stucco, wood, and concrete [8]. The climbing mechanism developed for DROP uses these microspine hooks because they provide a well tested and proven method of climbing. Microspine mechanisms require no power to maintain grip, are compact, and depending on design weigh comparatively little. Therefore, they are a logical choice for lightweight robots designed to operate in a wide range of natural and manmade environments. On DROP, these microspines are arranged in a completely new manner that allow climbing without complex mechanics while maintaining the ability to achieve rapid ground travel and easy transitions from horizontal to vertical and vice versa.

II. Design

A simple two-wheeled design was chosen to create this teleoperated vehicle with a high mobility and durable construction. This design has proven successful in robots such as Recon Robotics ThrowBot and NASA's Axle robot (Fig 4). It allows DROP to not only be produced and assembled quickly but it also lowers the complexity and associated weight of the robot.

A. Climbing

DROP implements a completely new climbing mechanism that combines established microspine technology with a simple rotary motion to achieve rapid climbing and easy transitions from horizontal to vertical surfaces.

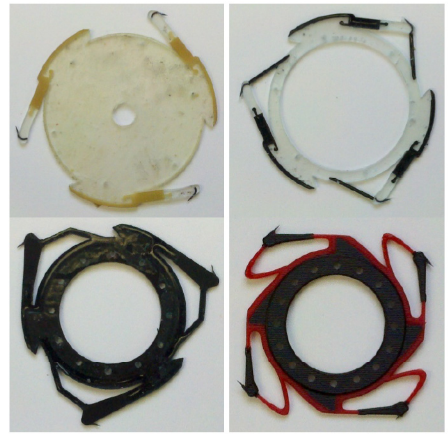

Fig. 2. Four iterations of microspine sprocket design. Moving horizontally from top-left to bottom-right, iterations 1-4 are displayed.

DROP achieves its vertical mobility through the use of wheel-like microspine sprockets. Microspines, referred to throughout this paper as simply hooks, were chosen because they provide a low mass, low power solution to climbing. Robots which successfully employ microspine climbing mechanisms include Stanford's RiSE and Spinybot (Fig 1). Creating a circular array of these microspine hooks, each with an independent flexible suspension, allows continuous engagement with the climbing surface using a straightforward rotary motion (Fig 2). The suspension feature enables each microspine hook to engage the surface independently of other hooks. The flexibility of the suspension then allows the microspine hook to remain engaged as the sprocket rotates through a greater range of motion then would otherwise be possible with a rigidly mounted system.

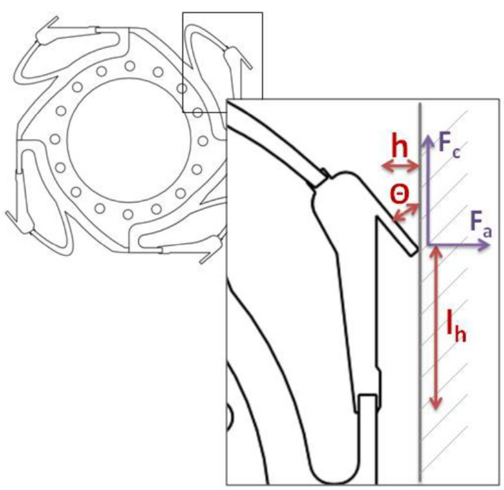

Fig 3. F.B.D. of microspine sprocket design displaying variables Θ, l_h, r and forces F_a & F_c

The primary consideration when designing these sprockets was the engagement angle of the microspine hook with respect to the climbing surface, denoted as **Θ** in figure 3. An engagement angle of between 30° and 45° has shown to be ideal to maximize the ratio of climbing force (**F_c**) to adhesion force (**F_a**) (Provancher paper). Since the continuous rotation of the sprocket during travel results in a continually changing of hook angle the overall design of the sprocket was greatly influenced by the need to limit the hook engagement angle. To address this, several variables were taken into account. Working from the assumption that the hook housing initially engaged parallel to the surface and proceeded to rotate in a direction that would to increase **Θ,** we set **Θ = 30°** and **l_t** and **h** such that the maximum rotation of the hook housing is limited to 15°; thus creating the desired range of hook angles between 30° and 45°.

Choice of flexure shape and stiffness was based on this desired hook angle and several additional factors determined through experimental testing. Fig 2 shows the 4 iterations of sprocket design, from the initial version in the top left to the final iteration in the bottom right. For initial prototyping, two materials were considered for the flexure segments, one of hardness Shore 20A and the second of hardness Shore 60A. Those sprockets constructed of Shore 20A hardness exhibited desirable extension characteristics; however, they were substantially more prone to over extending away from the sprocket and entangling with other hooks. In addition, the softness of the flexure material prohibited hook disengagement and often resulted in failure due to the flexure ripping at the attachment point the harder hook housing. Those constructed of Shore 60A hardness were not as desirable for flexure extension but they did not exhibit many of the issues of the Shore 20A flexures; therefore, these flexures were chosen for the final version of DROP.

The side-by-side arrangement of sprockets was also determined via experimental testing. Many arrangements were tried in an attempt to eliminate issue such as entanglement and twist. As mentioned previously, entanglement was the tendency of hooks to extend and engage adjacent hooks. This greatly hindered the engagement of the hooks with the climbing surface. The addition of the support flexure in versions 2-4 greatly reduced this issue, although, it introduced the issue of twist. Twist was the tendency of the hook housing to rotate out of the plane of the sprocket. This effectively eliminated the chances of a hook engaging the surface as it would often end up parallel with the surface instead of the desired perpendicular engagement. Twist was a more complex problem to resolve and the final version of DROP combines an exaggerated support flexure to allow increased motion in the plane of the sprocket as well as dividers between each sprocket to constrain the motion of the hook housing to the plane of the sprocket.

B. Body

Considerations for the body design included low weight, impact absorption, and mobility. The body is constructed from materials that are lightweight and durable. The strategic use of impact dampening materials, such as polymers in the Shore 20A-60A hardness range, serve to reduce the impact forces seen by the controls, those parts most susceptible to impact failure.

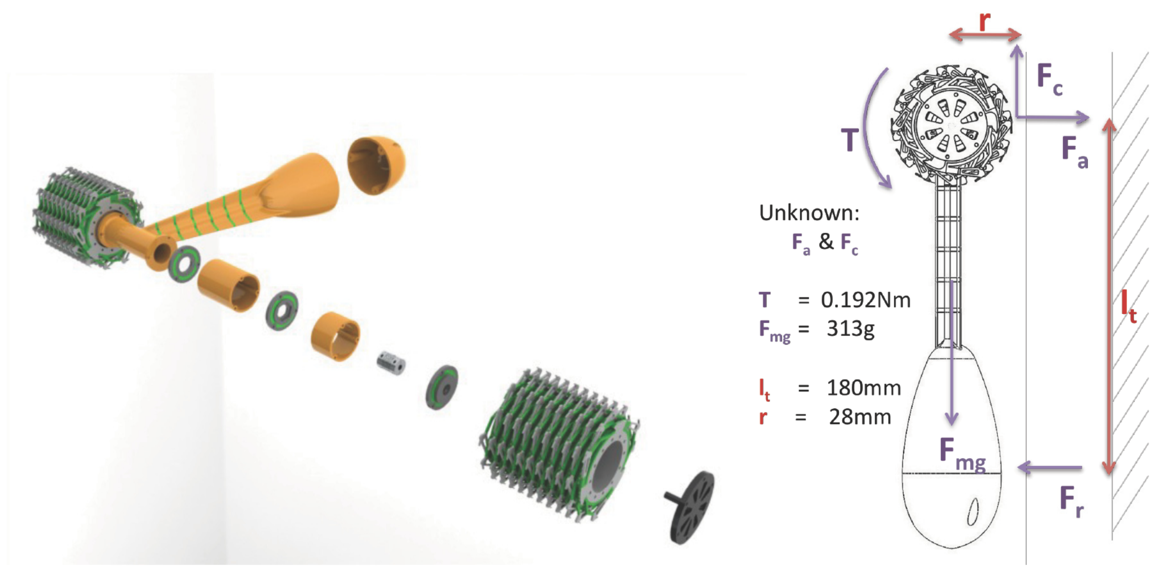

Fig 4. Left, Exploded view of DROP body design. Right, F.B.D. of DROP during climbing operations with known and unknown variables.

The body of DROP is constructed from the 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 (Fig 4). The center and tail sections are connected by alternating sections of SLS material and a polymer of Shore-60A hardness. These alternating sections of hard and soft operate much like the vertebrae in a spine, allowing the tail to bend and twist relative to the central section. Because they are not rigidly connected the two sections are capable of absorbing impacts independently.

C. Controls

The controls found on DROP are simple and direct. Two motors provide 192 mNm of torque, sufficient for robot to climb at a weight of up to 400g. An ATmega328 microcontroller is used to control the motion of the robot, making it possible to accurately manipulate the rotation of the microspine sprockets depending on user or sensor input. Doing so enables DROP to use one motor control algorithm for ground travel at high speed and another for more controlled, secure climbing. 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 back provides DROP with approximately 20 minutes of mission life.

III. Results

Achievements for this project include the ability to transition from horizontal to 90° vertical surfaces, travel at a ground speed of 45cm*s^{-1}, and climbing concrete faces up to 85° at approx 25 cm*s^{-1}.

Horizontal to vertical surface transitions were achieved with a high degree of success and repeatability. These transitions were possible at a variety of speeds, including full throttle. Transitions from vertical to horizontal, however, were not possible with the current body design. The mass of the controls at the end of the tail in conjunction with the stiffness of the tail completely prohibited this transition due to the large moment they created.

The climb speed and ground speed of DROP were both above the initial goals. The ground speed of 45cm*s^{-1} was 50% above the initial goal of 30cm*s^{-1}. Additionally, the climb speed on an 85° inclined surface was estimated to be 25cm*s^{-1}, a relatively high rate of speed when compared to other microspine climbing robots.

While impact testing and durability were not tested extensively due to time constraints, DROP was shown to be capable of surviving falls when driving off a roof at 3m onto concrete surfaces. DROP was also shown to be equally as durable when thrown onto a roof of 4m height. During falls from the 4m roof the robot failed to survive. This failure is attributable to material choice and design of the end cap that connects the sprocket array to the drive axle.

The audio/video payload and UAV deployment were not included or tested in these first iterations of the robot as efforts were concentrated on climbing and durability research.

IV. Discussion

The accomplishments described in the results section have shown the promising potential of DROP. While improvements can be made to the weight, durability, and climbing ability of the robot there have been significant strides made in the initial iterations.

DROP has met several goals that were previously unachieved in robotics. No other robot is capable of making rapid transitions from horizontal to vertical surfaces like DROP. These transitions are an important part of creating a useable robot that has functionality in real world scenarios. Achieving near vertical climbing using a wheel like design has been accomplished in other robots; however, none of the robots using this design are capable of climbing concrete or stone surfaces. The durability exhibited by DROP is also rarely seen in other climbing robots. Survivability during falls from roof height (3m) and when thrown onto roofs is an important feature that allows the robot even greater functionality in comparison to existing designs.

A few of the issues that remain with the platform include the inability to climb completely vertical surfaces, the lack of a useable payload and the relatively low durability when compared to the desired durability. Difficulties encountered with climbing are thought to be the result of several factors. The most important of these being body design. The two wheeled body design is beneficial for low weight and durability; however, it creates a reaction force on the tail that drives the robot off the wall. Addressing durability, the failure of DROP from 4m was caused by a single part that can be easily reinforced by altering the design slightly or selecting a more elastic material. This will likely be a simple and quick fix that will go a long way toward increasing the survivability of the platform. The audio/video payload was not included in these initial versions of the platform in favor of better addressing climbing and durability, but it has been designed and could be easily added.

Future Research

The direction of future research for DROP includes the continued design of the sprocket mechanism, a redesign of the body structure, and more quantitative testing on all aspects of the robot. At this stage in the project the body design is the primary component of the robot determining climbing ability. The body will be evaluated and redesigned until 90° vertical climbing is achieved reliably. The key concern for sprocket design in the future will be the reduction of weight. The general design of the sprockets is highly functional but the amount of mass in each sprocket is far too high for the long term goal of reaching 100 grams. Along this vein, other designs and materials will be explored in future research. Once a durable iteration capable of reliable vertical climbing is achieved the project will then move into a more quantitative test phase. Gathering data on all aspects of DROP will further influence the design and implementation of the robot in the long term future.

Acknowledgements

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by North Carolina Space Grant and the National Aeronautics and Space Administration

References

1. M. J. Spenko, G. C. Haynes, J. A. Saunders, M. R. Cutkosky, A. A. Rizzi, R. J. Full, and D. E. Koditschek, “Biologically inspired climbing with a hexapedal robot,” *Journal of Field Robotics*, vol. 25, no. 4-5, pp. 223–242, 2008.

2. M. P. Murphy, W. Tso, M. Tanzini, and M. Sitti, “Waalbot: An agile small-scale wall climbing robot utilizing pressure sensitive adhesives,” *in IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2006, pp. 3411–3416.

3. http://www.irobot.com/gi/ground/

4. M. Barnes, H. Everett, and P. Rudakevych, “Throwbot design considerations for a man-portable throwable robot,” in *Proceedings of the SPIE Unmanned Ground Vehicle Technology VII*, Orlando, FL, Mar. 2005.

5. Birkmeyer,P., Peterson, K., and Fearing, R.S, “DASH: A Dynamic 16g Hexapedal Robot”, *IEEE International Conference on Intelligent Robots and Systems*, 2009.

6. Xiao, J.*,* Sadegh, A.*,* Elliott, M.*,* Calle, A.*,* Persad, A.*, and* Chiu, H. M., *“*Design of mobile robots with wall climbing capability.” In Proceedings of the 2005 IEEE/ASME *International Conference on Advanced Intelligent Mechatronics (AIM'2005)*, July 2005, Monterey, CA.

7. Silva, M.F. Machado, and J. Tar, J.K. “A Survey of Technologies for Climbing Robots Adhesion to Surfaces.” *IEEE International Conference on Computational Cybernetics (ICCC*). Nov, 2008.

8. Asbeck, A.T., Kim, S., McClung, A., Parness, A., and Cutkosky, M.R., “Climbing Walls with Microspines", *IEEE International Conference on Robotics and Automation (ICRA*), May 2006, Orlando, FL, USA

9. Parness, A., Asbeck, A., Dastoor, S., Fullerton, L., Esparza, N., Soto, D., Heyneman, B., and Cutkosky, M., “Climbing rough vertical surfaces with hierarchical directional adhesives," *IEEE International Conference on Robotics and Automation (ICRA),* 2009, 2675-2680.