8/25/2017
Andrew Edoimioya
SURI Project Summary, Summer 2017
Biomimetic and Dexterous Laboratory
Department of Mechanical Engineering, Stanford University

Super SCAMP: Relevant Scaling Considerations for Perching and Climbing with a Multimodal Robot

1. Introduction and Motivation

The Stanford Climbing and Aerial Maneuvering Platform (SCAMP) is the first robot capable of flying, perching with passive technology on outdoor surfaces, climbing, and taking off again [1]. SCAMP was conceptualized, designed, and manufactured with funding as a part of the U.S. Army Research Lab's (ARL) Micro Autonomous Systems and Technology (MAST) consortium, which contains universities and research laboratories across the world. This summer (Summer 2017), ARL is hosting technical demonstrations for all consortium members to display and demonstrate their work. As part of the consortium, Stanford University, more specifically the Biomimetic and Dexterous Laboratory (BDML) was asked to participate in the demonstrations.

While preparing for the demonstrations, we found that the original SCAMP platform would not be suitable for the demonstration for a few reasons. In particular, we were unable to stabilize the flight of SCAMP's quadrotor due to how the mass of the climbing mechanism was distributed. Additionally, the perching, climbing, and take-off mechanisms of the platform did not prove to be reliable enough for a demonstration of this magnitude. We, thus, decided to scale the platform to provide more robustness for the demonstration. By increasing the thrust capacity of the quadrotor (and simultaneously increasing its size), we would be able to stabilize and control its flight with great accuracy. An increase in the size of the quadrotor also meant that we needed to consider the ways the increased weight, length, and other factors would affect the perching and climbing of the robot.

2. Definition of the Problem

The original SCAMP robot weighed a total of 38 g, while we estimated that Super SCAMP would weigh about 150 g, almost four times more (see **Fig. 1**). [Super SCAMP actually weighed 163 g as of August 22, 2017.] The mass difference meant that we would need to change the servo motors that were used to actuate the mechanism to provide more torque than the previous motors. The increase in mass also constituted changes in the design, number, and size of the microspines that were necessary to reliably perch and climb with the Super SCAMP platform.

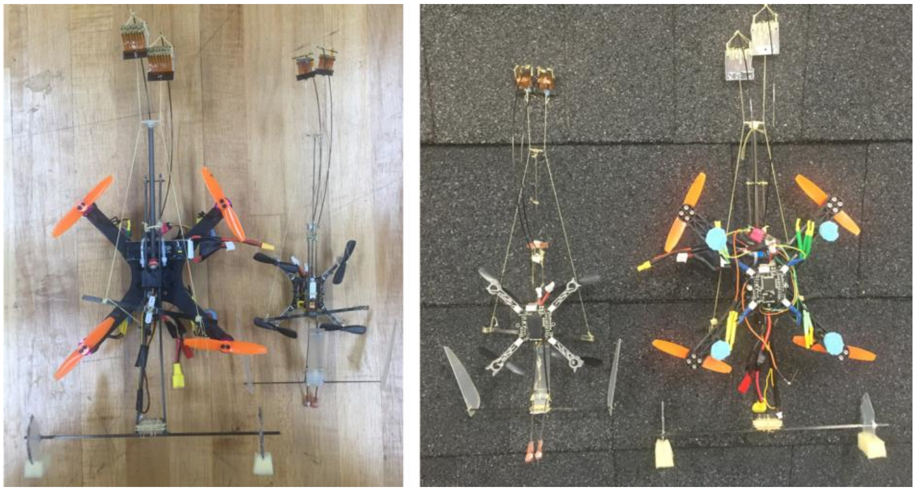

Figure 1. Side-by-side comparison of SCAMP and Super SCAMP.

A bigger quadrotor also required changes to the dimensions of the climbing mechanism (hereafter referred to as the mechanism). The characteristic length, L, of the quadrotor was determined by the side length from rotor to rotor on the quadrotor (see **Fig. 2**). It is important that the base/bottom of the mechanism is at least as long as the characteristic length of the quadrotor to maintain a flat stance on the wall during perching and crawling by preventing unwanted moments on the platform during movement. Additionally, L helped us determine the lengths of the rest of the mechanism's body as the feet must be located to maximize the downward force on the microspines, while maintaining the compact nature of the mechanism.

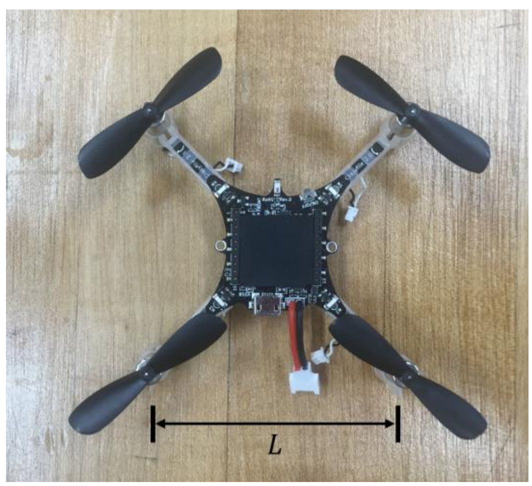

Figure 2. Characteristic length of the quadrotor.

Our approach to designing Super SCAMP's mechanism was iterative. We began by designing the body of the mechanism using SCAMP's mechanism as a guide, scaling dimensions where it was necessary and appropriate, and then iterating on the dimensions and materials until we reached a robust solution. Similarly, we began with the microspines that were used on the SCAMP platform and iterated appropriately. In Section 3, we will discuss the iterations of the mechanism's body, detailing our reasoning for making changes in each iteration. Complimentarily, Section 4 will discuss the iterations of Super SCAMP's microspine design. Finally, in Section 5, we will conclude with qualitative results from both iterations as well as recommendations for future work related to scaling the platform.

3. **Scaling the Body of Super SCAMP's Climbing Mechanism**

The first iteration of the climbing mechanism was designed by purely scaling the significant parameters of the original SCAMP mechanism with characteristic lengths using the same carbon fiber materials to fabricate each section. We determined the characteristic length of the Crazyflie, SCAMP's quadrotor (see **Fig. 3**) as well as the dimensions of SCAMP's mechanism (**Fig. 4*(a)***). The base of SCAMP's mechanism, b_1, was 12.7 cm and the Crazyflie's characteristic length, L_1, was 6.7 cm. Thus, the base length was 6 cm longer than L_1 and, when centered, this meant 3 cm of the base was outside each end of the L_1. The first iteration of Super SCAMP's quadrotor had a characteristic length, L_2, of 16.5 cm. Thus, we set the base length, b_2, at 22.5 cm, 6 cm greater than L_2, also allowing 3 cm of the base outside each rotor. After setting b_2, we then scaled some of the carbon fiber sections that made up the remainder of Super SCAMP's body proportionally with respect to the base frame length. For example, the main frame of SCAMP's body was 15.9 cm, approximately 1.25 times the length of its base, b_1. Thus, we set the main frame of Super SCAMP's body to be 28.2 cm, which is also approximately 1.25 multiplied by b_2. Other dimensions were kept the same or changed based on intuition, but not necessarily scaled. **Fig. 4*(b)*** shows the other dimensions used for Super SCAMP's first climbing mechanism.

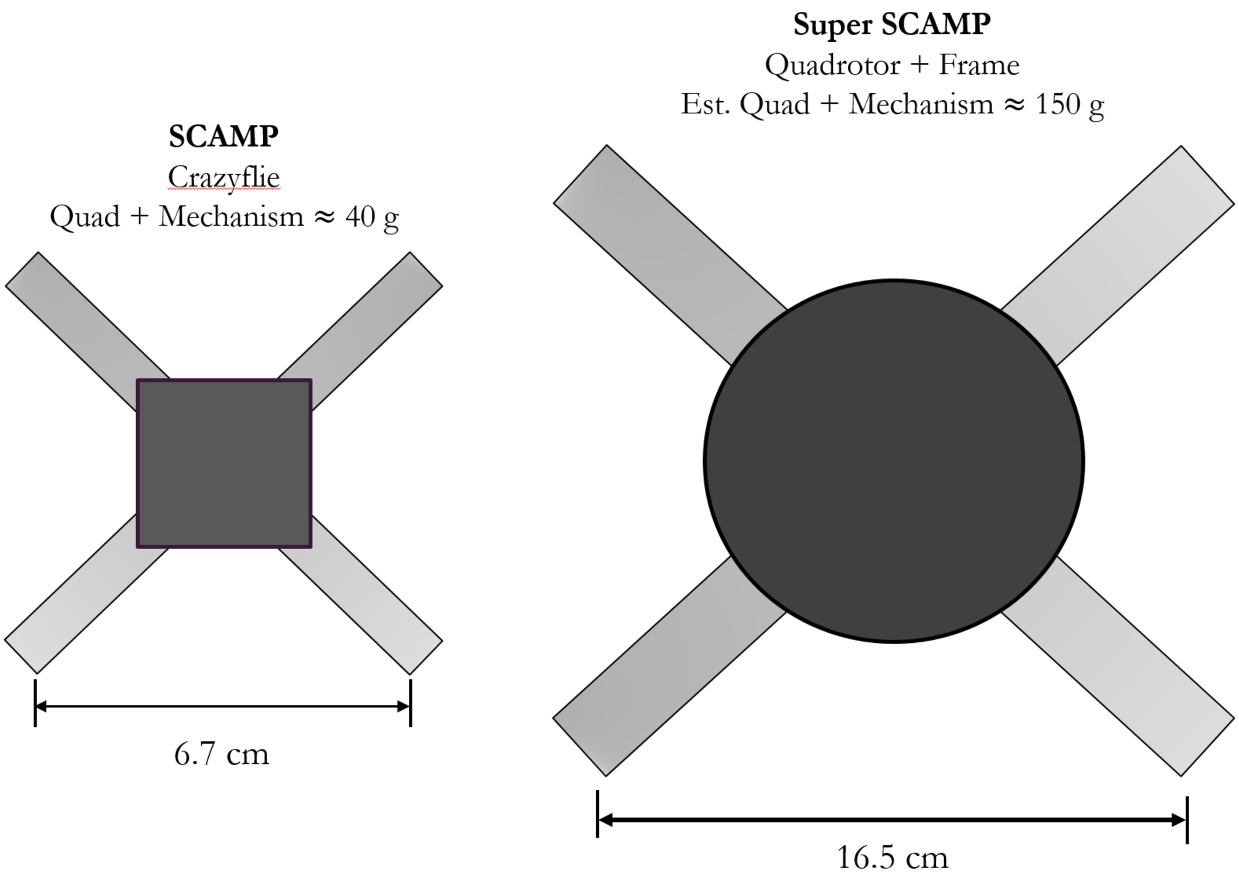

Figure 3. Quadrotor comparison of SCAMP and Super SCAMP.

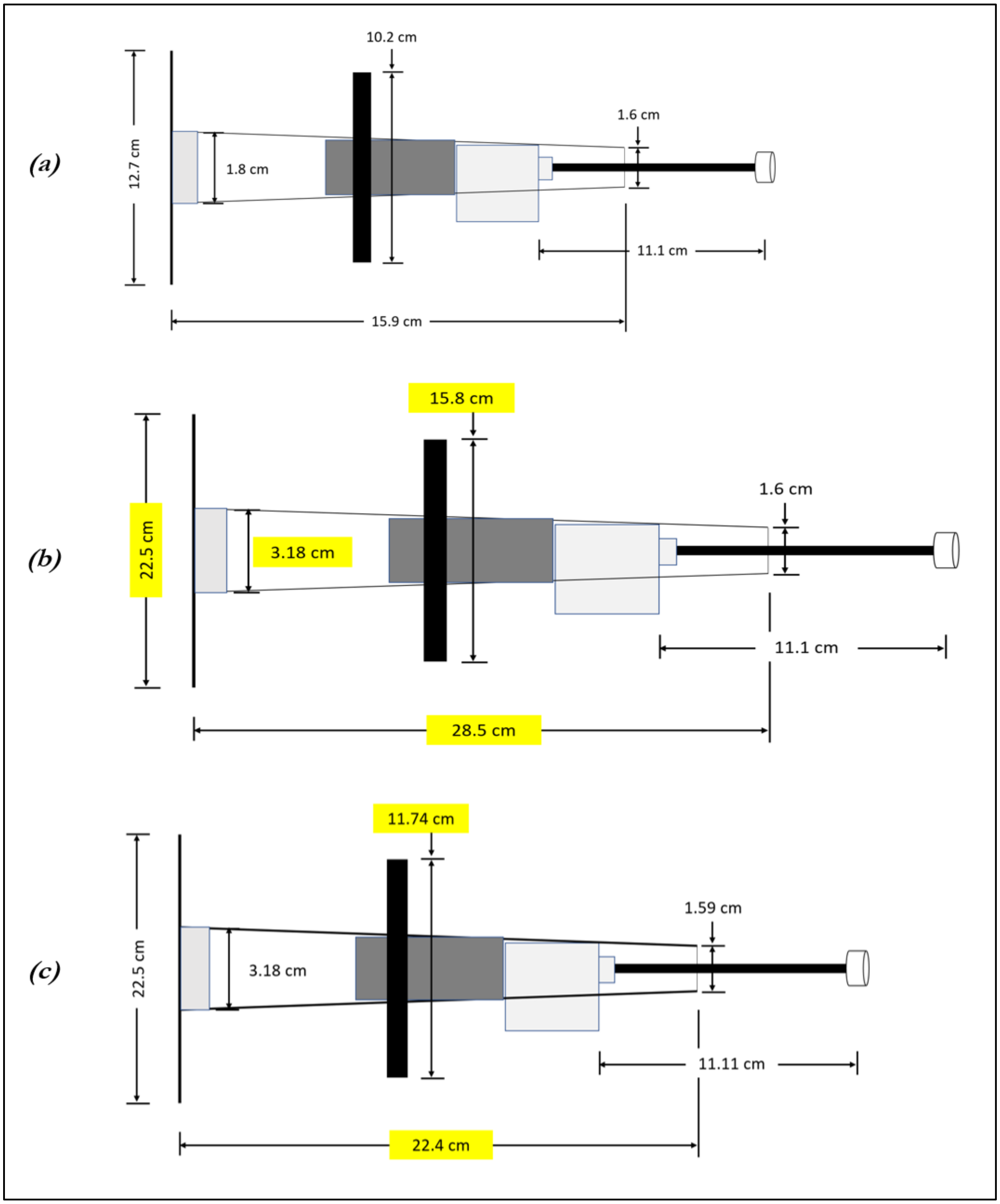

Figure 4. Dimensioned schematics climbing mechanisms: ***(a)*** Original SCAMP mechanism, ***(b)*** first iteration of Super SCAMP mechanism, and ***(c)*** second/final iteration of Super SCAMP mechanism. Changed dimensions from each iteration of the Super SCAMP mechanism are highlighted.

After completing the first mechanism, we attached it to the quadrotor and tested its flight. We quickly found that there was a problem with the mechanism that was causing the quadrotor to be unstable in flight. The body for the mechanism was too long and too flexible in the torsional direction as it was made from 1.5 mm-thick carbon fiber stock sections. We noticed that the vibrations from the quadrotor was causing the mechanism's body to be excited into its resonance vibration modes. This disturbance then, in turn, affected the quadrotor by adding an external disturbance to the system that could not be stabilized. In order to continue testing, we shortened the length of the body and added some structural support to increase its rigidity. This seemed to work well and reduced the induced vibrations making it possible to perch with the first mechanism. In fact, we demonstrated Super SCAMP's ability to perch at one of the workshops of the Living Machines Conference, held at Stanford University in the summer of 2017.

The second iteration of the climbing mechanism kept a lot of the initial features of first one. The most significant change was the design of the body. The second time, we used a shorter, thicker variation of the carbon fiber stock in an effort to remove the vibrations found in the first model. We also reduced the length of the extend/retracted arm that sits atop the servo motor. This change decreased the likelihood that the arm makes contact with a wall asperity while climbing and also reduced the overall weight of the mechanism, which we were conscious of doing during the second build. **Fig. 4*(c)*** shows the dimension changes that were made to the second Super SCAMP climbing mechanism from the first.

4. **Microspine Designs to Accommodate Increased Weight**

The design of the microspines on the platform is an important aspect of its functionality. Through observing the SCAMP's climbing motion and studying the engagement of the spines with asperities in the wall [2], [3], we gained some practical insights to designing the spines. The spines needed to be compliant in both the torsional direction and in their engagement with the wall. The torsional compliance allows the spines to rotate into an even-loading position (i.e., all spines directly against the wall) regardless of the approach angle of the foot. At the point where the spines contact the wall, each foot must also be compliant enough to be pushed back to allow other spines to come into contact with the wall before the spines are loaded. The spines must also be spring loaded so that they return to their original and most favorable position after each step.

To establish a baseline for the strength of the microspines, we used a set of the original microspines from SCAMP, as seen in **Fig. 6**, on the Super SCAMP mechanism. After testing these spines with the expected weight of our system, we found that they would not be able to support the weight. They disengaged with the wall every other step and were damaged by the wall at times.

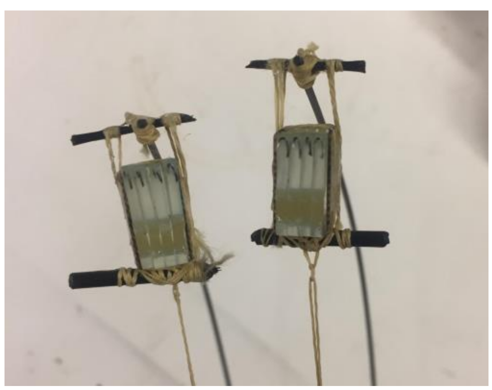

Figure 6. Original SCAMP Microspines.

For the second iteration of the design, we decided to double the number of spines and manufacture the backing of the feet out of Kapton. Kapton gave us the luxury of a tougher material in the axial direction that was compliant enough to spring-load the spines. We achieved the requirement of compliance of each spine on the foot by laser cutting slits between each spine (see **Fig. 7**). This second design was robust enough to hold the weight of Super SCAMP while it was perching but was not able to support it while scaling the wall. The flat design of the foot made it difficult for the spines to adhere to asperities on the wall before the bottom of the foot made contact with the wall, gently pressing against wall and causing some spines to disengage.

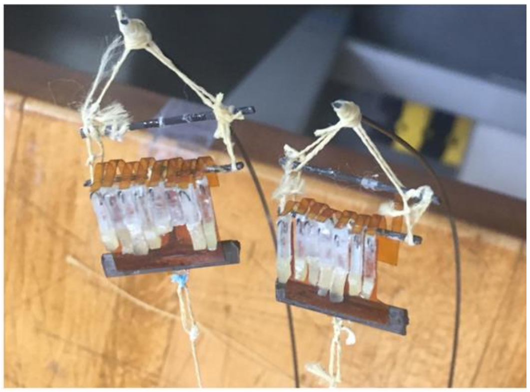

Figure 7. Second iteration of Super SCAMP Microspine design.

The third iteration of the spine design was simply an expansion of the original SCAMP microspines. Since the microspine design was tremendous successful and robust on the original SCAMP platform, we decided to revisit the design to see what we could learn from it. In particular, we believed the compliance that the spines provided in the normal direction (allowing forward spines to move backwards to allow more spines to contact the wall) was an extremely important design consideration to improve Super SCAMP's climbing. Instead of the traditional four-spine foot design, we designed eight-spine feet in a similar manner, as seen in **Fig. 8**, but ran into most of the same issues as the initial spines. Although also robust with regard to perching, the design didn't seem to have enough toughness in the axial direction to hold the Super SCAMP's weight while climbing. We saw Super SCAMP take a few steps (about 3 or 4) during each test before the spines disengaged from the wall,

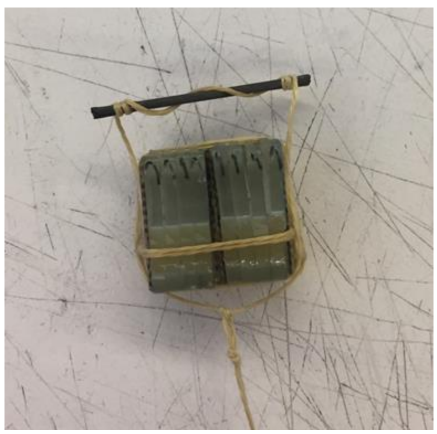

Figure 8. Third iteration of Super SCAMP Microspine design.

The final design of the microspines was an aggregate design, utilizing all the lessons learned while designing the other spines. We used bigger fishing hooks for our spine design and attached them to laser cut Kapton (see **Fig. 9**). These spines had a resting curved profile, which we learned was useful from the second design. The spines are also adhered to the back of the Kapton taking advantage of both the Kapton's axial strain strength and the spine's curved surface profile. These feet had not been tested as of August 24, 2017, but we are confident that we will see improvements in the climbing of the robot from this spine design.

Figure 9. Final iteration of Super SCAMP Microspine design

5. **Conclusion and Future Work**

Our work this summer set the foundation for scaling the SCAMP platform, allowing us to expand its application capacity. A larger platform allows for more stable flight in areas where external disturbances might adversely affect the smaller and lighter platform. Super SCAMP allowed us to study and begin to understand the dynamics and critical parameters of the perching and climbing mechanism of the platform. After two design iterations of the perching and climbing mechanism's body, we settled on a light and durable design that prevents the mechanism's body from adding external vibration disturbances to the quadrotor's flights, allowing us to maintain stable flight until perching. Once perched, we developed a robust microspine design using 0.05-inch Kapton sheet that is compliant in the normal direction to allow individual spine movements, but stiff in the axial direction to support the weight of the new platform. The larger spines on the platform will increase the likelihood of successful perching and climbing on surfaces with larger-sized asperities, such as the roofing shingles we are using for the experiments during this project.

The knowledge gained over the course of this project should be utilized to continue improving the current mechanism and microspine design of Super SCAMP. Future work for this project may include continuing to scale the platform to even larger quadrotors in order to determine the weight limits and constraints on perching and climbing with spines. This may also open doors to discovering other methods for adhering to vertical surfaces and/or understanding the impact of the size of the individual spines (or fishing hooks) used in applications. It would also be useful to devise a quantitative method to determine the number of spines necessary for successful perching and climbing mechanisms across different scales of quadrotors.

6. **Acknowledgements**

I would like to thank Professor Mark Cutkosky, Andrew F. Bell, Alessandro Diodato, and other members of the Biomimetic and Dexterous Manipulation Lab (BDML) for their technical assistance, support, and guidance throughout this project. I would also like to thank the Summer Undergraduate Research Institute (SURI) at Stanford University for providing the funding that led toward the completion of this project.

References

[1] M. T. Pope *et al.*, "A multimodal robot for perching and climbing on vertical outdoor surfaces," *IEEE Trans. Robot.,* vol. 33, no. 1, pp. 38-48, February 2017.

[2] A. T. Asbeck, S. Kim, M. R. Cutkosky, W.R. Provancher, and M. Lanzetta, "Scaling hard vertical surfaces with compliant microspine arrays," *Int. J. Robot. Res.*, vol. 25, no. 12, pp. 1165-1179, 2006.

[3] A. T. Asbeck and M. R. Cutkosky, "Designing compliant spine mechanisms for climbing," *ASME J. Mech. Robot.*, vol. 4, no. 3, 2012, Art. No. 031007.