Design Optimization of Morphing Robots in Extreme Environments

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Summer 2024

1 Abstract

Throughout history, the human desire to explore the unknown has driven countless expeditions to the world's most extreme and unforgiving environments. From the depths of the oceans to the peaks of towering mountains, humans have continually sought to push the boundaries of what is possible. With the advent of advanced technologies, our ability to explore has expanded far beyond what was once imaginable, enabling us to access regions that would otherwise remain unreachable.

Among the most significant technological advancements has been the development of robotics, which has revolutionised the way we approach exploration. However, many conventional robotic systems are outdated, overly complex, and prohibitively expensive. Their large, heavy designs often limit their adaptability and efficiency, making them less suitable for extreme and chaotic environments.

There is a growing need for a new generation of robots—ones that are lightweight, energy-efficient, and versatile enough to withstand the harshest conditions, from polar ice fields to volcanic landscapes. These robots must be capable of remote operation and capable of adapting to unpredictable terrains while minimizing the need for direct human intervention. This new class of exploration robots holds the potential to redefine how we gather data in extreme environments, ensuring that our exploration efforts continue to advance in both capability and sustainability.

2 Introduction

EPFL's Computational Robot Design and Fabrication Lab (CREATE Lab) throughout the work of PhD candidate Max Polzin has been working on this since its creation. Aiming for a lightweight, affordable and easy-to-use robot for harsh environments, the idea of an exploration robot with morphing capabilities appeared: G.O.A.T. (Good On All Terrain).

The principles behind it are simple. Making use of the fibreglass's extreme flexibility, additional degrees of freedom (DOF) can be reached by actuating winches placed in strategic locations of the frame. This enables not only countless geometrical configurations but also helps to change the centre of mass of the robot and therefore the robot's interaction with its surroundings, drastically reducing the number of failure modes and the need for direct human intervention.

My objective for the Summer was threefold:

- enhance teleoperation through the use of a first-person view (FPV) camera and by ensuring reliable data transmission over long distances,
- gain a deeper understanding of the different parameters of the robot,
- and build the prototype that I tested together with PhD candidate Nana Obayahsi and postdoctoral researcher Kieran Gilday as the result of a collaboration between our lab and Professor Keiji Nagatani from the University of Tokyo.

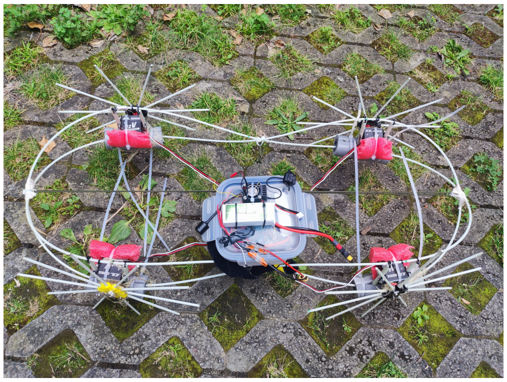


Figure 1: Old prototype

3 G.O.A.T. - General architecture

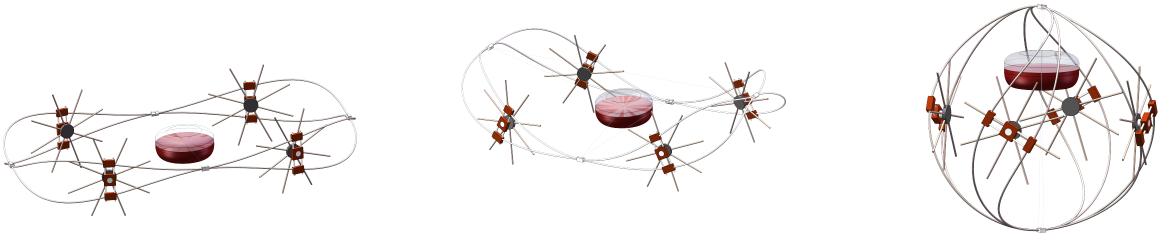
The essence of G.O.A.T. is its simplicity and its low-cost.
All mechanical parts are either fibreglass rods or 3D-printed pieces. Every version of the robot has at least the following features: a fibreglass frame, a payload constrained by ropes connected to the frame, and four independent rimless wheels.

Many parameters can be changed depending on the application: the thickness and length of the frame and spokes, the location and number of winches, the number of spokes for the rimless wheels, adding TPU ends to the spokes to reduce vibrations and so on.

The backbone of the robot consists of two identical circles of fibreglass rods held together by connectors and intermediate rods to mount the servomotors for the wheels, resulting in a strong and flexible frame.

Depending on how many additional DOFs we want to add, we can then replace the ropes holding the payload together with winches, enabling us to change the robot's geometry accordingly.

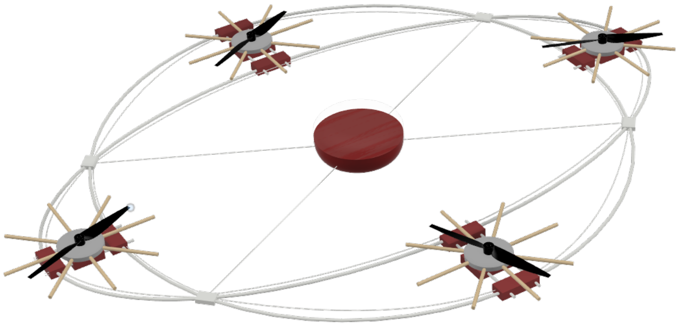
Such a system enables very complex geometries and configurations solely through the actuation of winches without changing parts.
The three main configurations are the driving, ball and flight configurations as shown in Figure 2.



(a)
Driving configuration,
no winch needed

(b)
Intermediate configuration,
one winch needed

(c)
Ball configuration,
two winches needed



(d)
Flying configuration, four winches needed

Figure 2: Main configurations of G.O.A.T.

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4 Japan architecture

4.1 Mechanics of the Japan prototype

For our field testing in Japan, I built a prototype with one additional DOF, i.e., one winch. We wanted to see whether morphing with only one DOF already helped to get unstuck. To hold the payload parallel to the ground for stable video transmission, I replaced the middle rope with an aluminium cross on which I fixed the payload.

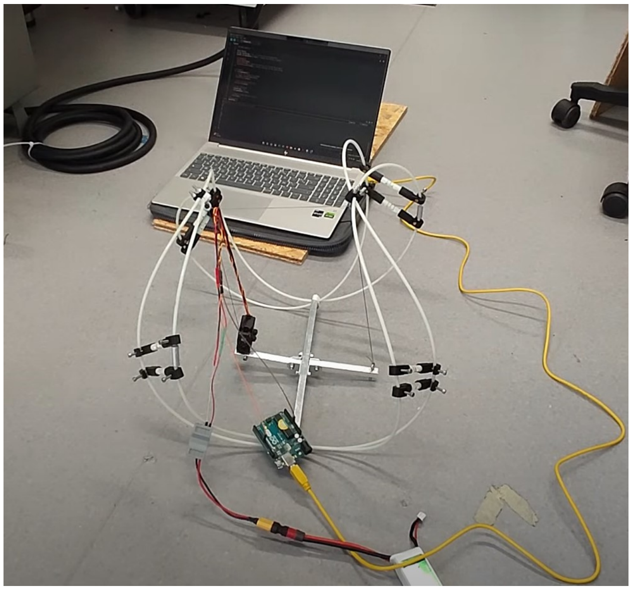


Figure 3: Morphing into ball configuration, note the winch on the left of the aluminium cross

4.2 Electronics of the Japan prototype

To enable remote operations, I integrated the DJI O3 Air Unit (AU), a FPV camera. Together with the DJI Goggles 2, they offer a live video transmission, enabling control of the robot without requiring a direct line of sight. By mounting the camera on a 180° servomotor, I expanded its initial field of view from 155° to 280°.
To effectively cool down the AU, I constrained it with heat sinks and DC fans as the AU would otherwise overheat in less than a minute.

(a) O3 Air Unit CAD

(b) O3 Air Unit integration

In addition to the scientific instruments, the payload includes the robot's electronics, specifically the microcontroller, battery, and telemetry modules (control and camera).

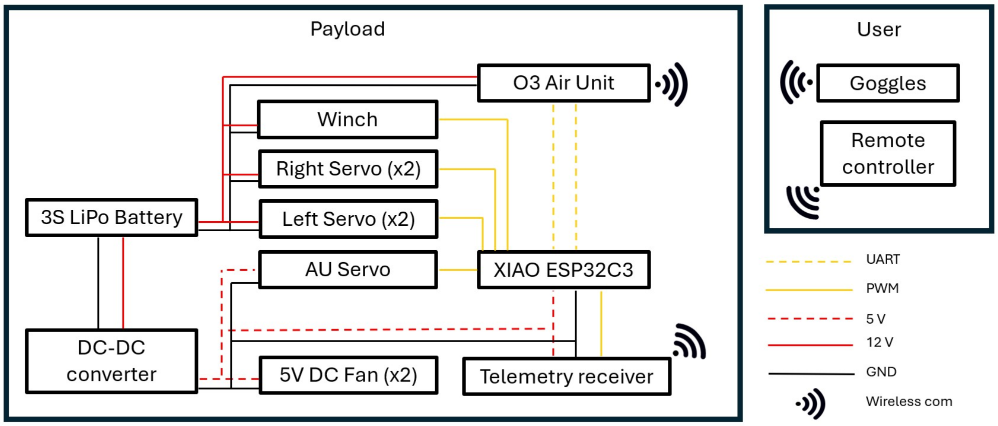


Figure 5: Schematic of the electronics and communications

5 Field Testing in French Jura

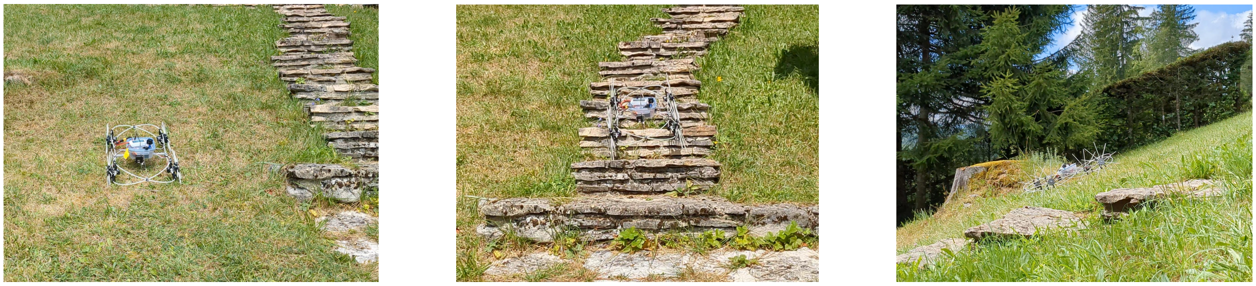
Two days before our trip to Japan, together with Nana Obayashi, we performed a one-day field test of the robot in the French Jura region. The main goal was to ensure that the entire system was ready for Japan. We also varied some parameters, such as different spoke lengths (10, 15 and 18 cm) and measured the effect of PLA ends on the spokes and the effect of sinking the horns into the wheel hub and adding an internal rim to prevent tall grass from wrapping around the servo.

5.1 First experiment - Stairs

In the first experiment, we measured the robot's ability to go up 30 degrees slopes and stairs (45 x 17 cm).

Spoke length	**10 cm**	**15 cm**	**18 cm**
Pros	- Very stable - No jiggling	- Most straight drive - Best control - Best spoke/frame ratio	- High clearance - Fast
Cons	- Low clearance - Slow - No veering	- Veers a bit - Jiggles a bit	- Not stable - Veers a lot - Frame jiggling

Table 1: Performance of different spoke lengths on 30° slopes and overcoming stairs



(a) 30° slope (10 cm) **(b)** Stairs (15 cm) **(c)** 30° slope (18 cm)

Figure 6: Each of the three spoke lengths was tested in all three situations (stairs, back and side view)

For our given configuration (rods of 2 m for the circles making the frame), the best spoke length was 15 cm, offering a good clearance and the best control. We therefore see that there is an optimal ratio between frame length and spoke length.

5.2 Second experiment - Forest

In this second experiment, we navigated in a forest-type terrain along a predefined path switching between 15 cm and 18 cm spoke lengths, both with and without rims. The addition of internal rims proved beneficial when overcoming obstacles like twigs, as they prevented the spokes from completely sinking into the branches. The only drawback of internal rims is that branches occasionally get stuck between them and the wheel hub. Morphing, even slightly, helped to free the spokes from the twigs.

With longer spokes (18 cm), it was significantly easier to manoeuvre over twigs compared to the shorter spokes (15 cm).

Control was also improved with the longer spokes as the robot was faster, making turns easier.

In all situations, sinking the servo horns into the wheel hub greatly increased the robot's ability to traverse tall grass, whereas previously even low grass would completely block the robot's motion.

(a) Spokes without rims (15 cm) **(b)** Spokes with rims (15 cm)

(c) Spokes without rims (18 cm) **(d)** Spokes with rims (18 cm)

Figure 7: Navigation through forest-type terrain

5.3 Third experiment - Driving up and down 40 degrees slopes

We then evaluated the spoke length influence on ascending and descending slopes.

Spoke length	**10 cm**	**15 cm**	**18 cm**
Pros	- Extremely stable - No tipping over	- More stable than 18 cm	- High clearance - Fast
Cons	- Low clearance - Slow - No veering	- Tips over if stopped during descend	- Tips over if stopped during descend - Difficult control when driving up - Frame jiggling

Table 2: Performance of different spoke lengths on 40° slopes

(a) 10 cm descent

(b) 15 cm ascent

(c) 18 cm tipping over

(d) 18 cm tipping over

Figure 8: Ascent and descent with different spoke lengths

The best control and most stable overcoming were achieved with 10 cm spokes, as the centre of mass was closest to the ground, preventing any tip-over. For the other spoke lengths, stopping during the descent resulted in tipping over due to inertia, which made it difficult to effectively control the robot.

5.4 Fourth experiment - PLA ends

The results of adding PLA to the ends of the spokes were quite disappointing as the robot had less traction, was much slower and overall less controllable. Consequently, we decided not to keep them for use in Japan.

Figure 9: PLA ends mounted on top of the spokes

5.5 Fifth experiment - FPV

In this final experiment, we controlled the robot solely through video transmission via the DJI Goggles. The results were very encouraging, as I was able to accurately determine the robot's position in space and navigate with ease. The only limitation at this point is the lack of a rearview (i.e., visibility of the back wheels).

Figure 10: FPV Navigation

5.6 Random selection of obstacles

With 15 cm spoke lengths, the robot was able to overcome 45° slopes and logs.

Figure 11: Overcoming 45° slopes and logs

6 Field Testing in Japan

There are approximately 1500 active volcanoes globally, with Japan being among the most volcanic regions, home to 111 active ones. Of these, 50 are particularly active, including Mount Asama. Currently, Mount Asama is classified at level 2 on the Volcanic Alert Scale. If the alert level rises to level 3, indicating a minor volcanic eruption, a 4-kilometer radius surrounding the volcano is rendered inaccessible. During such periods, it is essential to monitor the restricted area, particularly by analyzing volcanic ashes. When ashes combine with rain, it can trigger landslides, posing significant risks to the local population. The nearby village of Kita-Karuizawa, located downstream of Mount Asama, has built two “Sabou” (Japanese word for dams preventing landslides) to mitigate such risks.

By directly analyzing ashes from volcanic eruptions, authorities can better simulate and predict potential hazards, including the duration of volcanic activity, its intensity, and the pathways that ashes and mud may travel. Moreover, Mount Asama’s proximity to Tokyo—a metropolis with a population of 41 million—makes it particularly noteworthy, as volcanic ashes carried by the wind can easily reach the city.

While drones are currently used for monitoring, they face limitations in operational time (around 30 minutes autonomy compared to the desired 24 hours monitoring) and are unable to traverse the ground directly. Existing rovers and crawlers are also unsuitable, as they are too heavy, bulky, and lack the agility required to navigate the slopes around the volcano (approximately 30 degrees). In contrast, G.O.A.T. is lightweight, flexible, agile, and highly capable of traversing the challenging terrain at the foot of the volcano. Its flexible frame, modular payload, and ruggedness—able to withstand falls, rolls, and other potentially damaging events—make it particularly suited for deployment in such environments and this type of mission. Additionally, due to its lightweight design, G.O.A.T. can be transported by drone directly into restricted areas or could even start in its flight configuration before morphing back into driving mode once landed on-site.

Conducting a demonstration on Mount Asama is a significant and rare opportunity, as the area within the 4-kilometer radius is a restricted area for the public even at level 2. This allows us to showcase the robot’s versatility in a real-world environment, demonstrating its potential in emergencies rather than in simulated settings.

6.1 Day 1 - Mount Asama

On the first day, we took the Shinkansen from Tokyo Station and arrived around 10 am in Karuizawa where we took a car with Professor Nagatani and his assistant Yusuke Yasukawa to meet the rest of the team at the foot of Mount Asama. Our group consisted mostly of researchers from the University of Tokyo and employees from the geospatial company Kokusai Kogyo who were mainly responsible for logistics and safety and a drone company EAMS Robotics that operated the drone for transportation of the research experiments.

The geography of the site is as follows: a street separates the two areas for our experiments, Mount Asama on the left, and the dam on the right.

(a) Map of the area

(b) General meeting

Figure 12: Geography of the area and meeting with the team

After the general meeting (presentation, safety, tasks of the day) we started shuttling to the foot of Mount Asama.
While another scientific group used the drone to transport their scientific instruments (a ground station that measures different properties of ashes), we formed a group of 10 people to navigate with our robot on the volcanic terrain. We drove around mixed terrain ranging from sandy areas to very rocky terrain with 30 to 40-degree slopes. We had roughly one hour and a half to test our robot.

Once again, the only failures occurred in very thick grass and on steep slopes where the robot would tip over from time to time. The Japanese scientists were very excited about our robot as they had already tested different robots in the area, but none was as promising as G.O.A.T.

Figure 13: G.O.A.T. navigating around Mount Asama

(a) Experiment being transported with the drone **(b)** Mobile station to measure ash properties

Figure 14: Other experimental instruments

Figure 15: Setting up G.O.A.T.

6.2 Day 2 - Dam

On the second day, we went downstream to the dam to test the different wheels and measure the impact of morphing. The final goal was to simulate a short deployment mission with the drone.

Figure 16: Sabou - Dam to prevent landslides

We mainly conducted experiments in two areas. In the first one, we drove up 30-degree slopes before navigating over a small rocky path, using morphing when getting stuck. We repeated this experiment around 10 times.

(a) 30° slope

(b) Small rocky path

(c) Trapped in high-density grass

Figure 17: First experiments

For our second experiment, we extensively tested the robot in a very challenging terrain, climbing up a 35-degree slope via a narrow path to force the robot to overcome the obstacles and not navigate around them. We tested each set of wheels for around 15 minutes (5 attempts). Once again, as in the Jura region, the 15 cm spoke length was the most successful one, with 3 successful attempts out of 5. The 10 cm spokes were the most stable ones but we often lost traction by getting beached while trying to overcome obstacles. We had only one success. For the 18 cm spokes, controlling it was extremely difficult, as the robot would often tip over. As a result, we were not able to get all the way up.
Morphing didn't directly help overcome the obstacles but was extremely successful in getting the robot unstuck by bringing the wheels back to the ground or changing the robot's relative position to the ground. It was possible to get unstuck 8 times out of 10 and then continue the ascent by choosing a different angle of attack.

(a) Tipping over (18 cm)

(b) Tipping over (18 cm)

(c) Navigating on the back (15 cm)

(d) Beached (10 cm)

Figure 18: Narrow path on 35° slope

Finally, during a break between heavy rains, we found a 15-minute window to launch the drone and perform a dam inspection mission. I was standing on a hill and controlled the robot at a distance through the DJI Goggles. The drone was operated by the drone company. The mission consisted of a dam inspection, with G.O.A.T. being dropped at a precise location by the drone before navigating back to the launch site.

(a) Liftoff FPV

(b) Liftoff Ground Camera

(c) Mid-air FPV

(d) Mid-air Ground Camera

(e) Landing FPV

(f) Landing Ground Camera

(g) Descent FPV

(h) Descent Ground Camera

(i) Ascent FPV

(j) Ascent Ground Camera

Figure 19: Drone flight - Mission simulation

7 Conclusion

The purpose of the field testing around Mount Asama was to asses G.O.A.T's performance on volcanic terrain and simulate a real-world mission. The drone flight was in all aspects a success, as I was able to remotely control the robot back to the launch site after it was brought to a precise location by drone.

The remaining challenges that require further investigation are related to control and range of telecommunications.

On the control part, the current limitation arises from the use of skid steering, which presents difficulties in turning on the spot and restricts navigation. This issue may be addressed by implementing proportional speed control between the left and right sides of the robot.

Additionally, the robot exhibits slight veering due to the complexity of creating a perfectly symmetrical frame, as the four connectors that secure the fibreglass rods and the servomotors need to be precisely aligned.

Regarding telecommunications, the only remaining limitation is the range. Currently, we are restricted to a range of 1 km for video transmission and 2 km with the remote controller.

Further studies to find the best frame-to-spoke length ratio for a given environment will be very useful in tuning each prototype for its predefined application.

I am confident that the next missions in Greenland and the Himalayan Mountains will further showcase the wide range of applications of G.O.A.T.

8 Acknowledgements

Firstly, I would like to express my deepest gratitude to Lord Laidlaw and the Laidlaw Foundation for offering this exceptional research opportunity and for their generous financial support.

I am also immensely thankful to the entire EPFL CREATE Lab team, especially Professor Josie Hughes, PhD candidates Max Polzin and Nana Obayashi, and postdoctoral researcher Kieran Gilday, for their invaluable guidance and support throughout the entire process.

Lastly, I extend my sincere appreciation to the team for trusting me with the development of the Japan prototype and allowing me to take part in the field testing in Japan, which has undoubtedly been one of the most rewarding experiences of my life.