Portable Amphibious Spherical Rolling Robot with Live-Streaming Capability for Ground and Aquatic Deployment

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Abstract. Forested terrains and mudflats surrounded by water bodies such as rivers, lakes, and swamps are difficult to maneuver around, especially for man-made automations and robots. The lack of reliable robotic platforms often hinders operations such as search-and-rescue, surveillance, and research efforts made in these terrains. Whereas most developments are focused on improving maneuverability on either land or water, little has been done in developing robotic platforms with amphibious capability. To address this design gap, an amphibious spherical rolling robot design is proposed. A spherical rolling robot is advantageous in terms of its self-righting capability, balancing capability, and minimum damage to the surroundings during its mobilization. The proposed design contains a battery-powered fixed two-axis pendulum for the robots powertrain, which provides the robot with its self-righting capability. Two modular live-feed cameras are inserted to provide live-streaming capability, both of which can be easily replaced with other relevant sensors if needed. A custom-made 3D-printed sleeve is designed to improve the robot's propulsion on both land and water. Most of the robot's design features are highly modular, facilitating customization depending on the user's needs. With these configurations, the final prototype exhibited a high degree of maneuverability on both land and water. The live-streaming capability was proven with a video recording from the robot's cameras when deployed.

Keywords: spherical robots, amphibious, ecological and biological research, search-and-rescue, surveillance, modular.

I. Introduction

Global warming, climate change, rising sea level, and water pollution have all contributed to the increased importance of biological and ecological researches. At the same time, the increased frequency of commuting on commercial flights and sea voyages has called for reliable robotic platforms to aid in surveillance and search-and-rescue missions when disaster strikes. In both scenarios, the ability to explore remote areas is invaluable, especially forested regions and mudflats surrounded by water bodies such as rivers, lakes, and swamps. Nevertheless, current developments focus only on one of the two terrains – either land or water – with minimal development targeted towards the amphibious capability of robots.

The spherical rolling robot design is an ideal choice for the abovementioned applications because of (a) a sphere's symmetrical property, (b) potential in self-righting, (c) terrain versatility, and (d) its environmentally friendly nature. There is no preferred orientation when it comes to a sphere, and the neutral position of a spherical robot depends on the position of the robot's center of mass relative to the spherical shell. By choosing a proper driving mechanism, the problem of capsizing currently faced by many commercial designs can be fully nullified. Furthermore, a spherical robot moves by rolling on the surface it is placed on. With enough torque and traction it can virtually maneuver across any terrain without damaging the integrity of its surroundings [1].

Currently, the only two commercial spherical rolling robots with amphibious capability are the Sphero [2] and the Rotundus GroundBot [3]. The former is a toy made for young children, whereas the latter is heavy and designed more for ground surveillance. The Sphero, while portable, provides no meaningful capability for surveillance, search-and-rescue, and research. The GroundBot, on the other hand, is 60cm in diameter and weighs 25kg, which makes it bulky and difficult to deploy and retrieve.

II. THE ROBOT

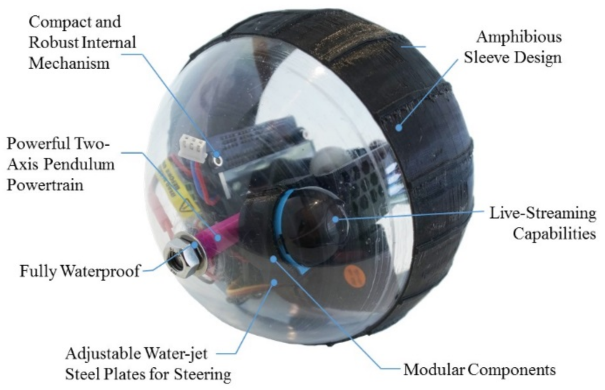


Figure 1. Salamander's Special Features

For the intended applications discussed above, it is important that the robot is small, light, portable and durable for ease of deployment and reliability. It must also exhibit sufficient mobility both on land and water, so that a change in terrain will not pose any problem to the completion of its task. It must also be able to house meaningful data collection apparatus, such as cameras capable of live-streaming, or sensors to gather useful data regarding its immediate surroundings. Lastly, it must be easily adaptable to the different tasks it may be deployed for, meaning that the sensors and cameras must be easily interchangeable.

III. DESIGN REQUIREMENTS

From Section II, the basic needs of a ground and aquatic surveillance robot can be summarized as follows: it has to be (a) portable and robust, (b) waterproof, and (c) amphibious (capable of water and ground propulsion). On top of these it has to (d) possess a modular internal mechanism for quick addition or removal of sensors and parts. The specific requirements are highlighted further in Section IV of this paper.

IV. DESIGN TARGETS

TABLE I. REQUIREMENTS AND TARGETS TABLE

#	**Requirement**	**Target**
1	The unit shall be able to withstand a drop from a height of 1 m above the water surface.	≥ 1m
2	The unit shall have a diameter of not more than 30 cm.	≤ 30cm
3	The unit shall weigh less than 1 kg.	≤ 1kg
4	The unit shall stay within 20˚ of its intended direction when entering a rough terrain (e.g. gravel grounds).	≤ 20˚
5	Minimum pendulum to overall mass ratio.	≥ 1:10
6	The unit shall be able to house two live-feed cameras.	2

Requirements 1, 2, and 3, mentioned in Table 1, serve as a means to gauge the ease of deployment of the robot. It is important that the robot can be easily deployed by an individual without any additional equipment. The height of 1m stated in requirement 1 is therefore chosen based on the average feet to waist height of a person, assuming that the robot is thrown at arm's length. A maximum diameter of 30cm is set in requirement 2 based on the largest ball used in a sport, the basketball, which is 25cm in diameter and is almost the largest sphere a person can hold with one hand. A maximum weight of 1kg is selected as the robot is expected to be portable and light enough to be carried manually without any additional aid.

Requirements 4 and 5 are devised to ensure that the robot is able to maneuver around the rough terrains it may encounter inside the remote operating areas. Requirement 4 ensures that the robot is controllable on any terrains, whereas requirement 5 ensures that the robot has enough steering capability to avoid objects and obstacles. The last requirement is to satisfy the need for live-streaming capability, as the robot is to serve as a reliable eye for its user during reconnaissance. The number of cameras to be mounted is fixed at 2 because the robot is to be able to monitor both the surroundings ahead of it as well as the surroundings under it, especially when on water.

These requirements formed the basis of the design, which is discussed in length in Section V of this paper.

V. DESIGN FEATURES

A. Powertrain: Single Two-Axis Pendulum

The powertrain of the proposed design involves a battery-powered two-axis pendulum mechanism. The main pendulum, powered by a microgear motor, drives the robot forward. The smaller, high density secondary pendulum that provides the robot with its turning capability is powered by a high torque servo [4].

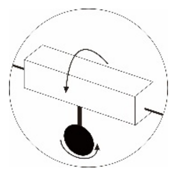


Figure 2. Powertrain Illustration

Based on Newton's Second Law for Rotation, equation governing the required gear ratio of the main pendulum is:

$$M_{Pm} l_{cgm} - \tau_m G = 0 \quad (1)$$

, where M_{Pm} is the mass of the two-axis pendulum mechanism, l_{cgm} is the distance of pendulum's center of gravity from the fixed axis, τ_m is the motor torque, and G is the gear ratio.

Estimating $M_{Pm} = 1\ kg$, $l_{cgm} = 10\ cm$, and selecting the 100:1 Pololu Microgear Motor as the benchmark motor choice, the required G value is 0.742. However, since the motor torque is proportional to the current output into the motor, a higher G

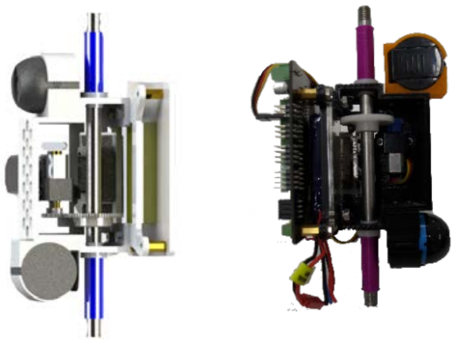
value of 3 is therefore selected to prevent excessive current drawn into the microgear motor.

Similarly, based on Newton's Second Law for Rotation, the governing equation for the secondary pendulum is:

$$M_{Ps} l_{cgs} - \tau_s = 0 \quad (2)$$

, where M_{Ps} is the mass of the secondary pendulum, l_{cgs} is the distance of secondary pendulum's center of gravity from the axis of the servo, τ_s is the servo torque. Since the secondary pendulum is to be mounted directly on the servo horn, no gearing is involved.

At 6.0V, the HS-422 servo selected as a benchmark has a stall torque value of 4.1 kgcm^{-1}. Hence, the maximum value for M_{Ps} is governed by the formula $M_{Ps} = \frac{\tau_s}{l_{cgs}}$. The longest possible value for l_{cgs} is the radius of the spherical shell. Therefore, maximum $M_{Ps} = \frac{4.1}{7.75} = 0.529$ kg, mounted at the edge of the spherical shell.



(a) (b)

Figure 3. Two-Axis Pendulum Mechanism. (a) 3D CAD Model Design. (b) Prototype of the Powertrain Subsystem.

From the calculations shown above, the 100:1 Pololu Microgear Motor is sufficient to drive the whole powertrain, and therefore it was selected together with the 3:1 gear ratio. To achieve this, a 20-teeth, 0.5 module Delrin spur gear is put on the motor shaft, whereas a 60-teeth, 0.5 module Delrin spur gear is mounted on the shaft. The HS-422 servo is also more than sufficient to power the secondary pendulum, which is targeted to have a mass of at most 100g (10% of the whole robot's mass). All these are housed inside a custom-made 3D-printed box. Two custom-made Delrin bushings are press-fitted coaxially on two opposing sides of the box, through which the 8mm steel shaft is inserted. The box is held in place by two custom-made 3D-printed spacers, and the 60-teeth spur gear is fixed on the shaft by a M3 set screw.

The secondary pendulum, made of mild-steel, is made using the water-jet. The modular design allows for easy addition or removal of weights on the secondary pendulum, facilitating fine-tuning of the sensitivity of the robot. This custom-made secondary pendulum is mounted directly onto the servo via a servo horn, completing the whole powertrain of the robot.

B. Live-Streaming: Modular Ai-Ball Cameras

The design of the custom-made pendulum box incorporates a 30mm x 25mm x 30mm space on each side for various sensors, such as the MPU6050 Triple Axis Accelerometer and Gyro Breakout and the HMC5883L Triple Axis Magnetometer. The current prototype utilizes these spaces to mount two live-streaming cameras.

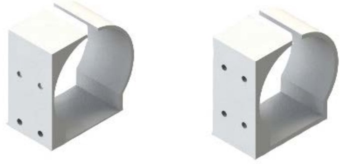


Figure 4. Modular Design of Camera Mount

The Ai-Ball cameras are used because of the user-friendly interface and affordability. To attach them onto the box, two 3D-printed mounts are designed to fit perfectly into the available space. M2 screws are used to secure the two mounts in place, providing modularity to allow ease of changing the cameras with other sensors depending on the intended use of the robot.

C. Shell Construction: Custom-made 3D-printed NinjaFlex Sleeve and Waterproofing

Figure 5. Assembly with Rubber Gasket

To achieve complete waterproofing of the shell, there needs to be a minimum number of holes used to secure the powertrain onto the shell. Hence, only one hole is to be drilled on each of the hemisphere that makes up the overall shell. The hole is to be the size of the shaft (8mm), and is drilled at the maxima of the hemispherical surface. The shaft is then secured between the two holes, and rubber gaskets are press-fitted against the exterior surface of the shell to prevent water from entering.

Figure 6. Custom 3D-Printed NinjaFlex Sleeve

To waterproof the gap between the two hemispheres, a custom-made 3D-printed elastic sleeve is fabricated. The elastic property is necessary to ensure that the sleeve presses against the exterior of the shell, completely preventing water from entering. Thus an elastic filament called NinjaFlex is used. When printed at a temperature of 220˚C with an optimal thickness of 0.75mm, the sleeve is able to stretch and press against the shell effectively.

As there is a need to improve propulsion on water, ridges are added into the design of the NinjaFlex Sleeve. Whereas a longer ridge will drastically improve the performance on water, such a design may worsen the performance on land. Hence, an optimum length of 1.75mm is chosen to achieve satisfactory performance on both land and water.

VI. Results and Discussion

TABLE II. Requirements and Test Results Table

Requirement	**Test Result**
The unit shall be able to withstand a drop from a height of 1 m above the water surface.	1m
The unit shall have a diameter of not more than 30 cm.	15.5cm
The unit shall weigh less than 1 kg.	807g
The unit shall stay within 20˚ of its intended direction when entering a rough terrain (e.g. gravel grounds).	15.6˚
Minimum pendulum to overall mass ratio.	1.5:10
The unit shall be able to house two live image feed cameras.	2

The test conducted comprised a drop test, driving test, buoyancy test, leakage test, and assembly test. Other requirements that did not need testing were verified through measurements or Solidworks CAD properties.

The final prototype has a diameter of 15.5cm and weighs 807g, allowing it to be carried and thrown with one hand. The Solidworks CAD property also showed that the pendulum to overall mass ratio is 50% higher than our target ratio of 1:10, which should give the prototype a better steering capability than initially intended.

Throughout the driving tests, the robot is capable of moving in its intended direction both on land and water considerably well. The slight deviations detected during testing were towards the left of the robot, meaning that the center of gravity is slightly more to the left of the robot. This was verified when the robot was able to move perfectly straight with a slight manual compensation to the right. Overall, the robot passed the driving tests well, and the minor misalignment of the center of gravity can be fixed with ease.

The unit was able to not only float, but pick up considerable speed when moved on water; proof that the ridges do improve the water propulsion of the robot. After driving continuously for 15 minutes, no leakage was spotted, verifying the functionality of the waterproofing mechanism. The unit was also able to withstand a throw from a height of 1m into the water, simulating its ability to be thrown by a standing person at arm's length into the water body.

The simple modular design of the mechanisms meant that assembly process was much easier than expected. It took on average less than 3 hours to fully assemble the robot with the tools commonly found in a workshop, and the only adjustment to be made is the position of the cameras inside the shell.

VII. Summary

The objective of the project is to design a portable and amphibious spherical rolling robot capable of live-streaming ability to aid in research, surveillance, and search-and-rescue missions on both land and water. The final prototype has exhibited performance far exceeding expectations in terms of its ease-of-assembly, water propulsion capability, and maneuverability. While the tests were conducted in a relatively controlled environment, the simplicity of the current design provides ample room for further fine-tuning and improvements. The modularity and substitutability of the camera mount design allow the user to easily replace the cameras and sensors for each particular mission. The design of the Sleeve may also be changed depending on the user's needs. All these equip the robot with the versatility required for deployment in forested areas, mudflats, or any remote locations deemed fit by the user that is surrounded by water bodies, whether for ecological and biological researches, or for surveillance and search-and-rescue operations.

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References

[1] J. Hernández, D. Sanz, G. Rodríguez-Canosa, J. Barrientos, J. del Cerro and A. Barrientos, 'Sensorized robotic sphere for large exterior critical infrastructures supervision', Journal of Applied Remote Sensing, vol. 7, no. 1, p. 073522, 2013.

[2] Gosphero.com, 'Sphero 2.0 | Connected Toy for iOS, Android, and Windows', 2015. [Online]. Available: http://www.gosphero.com/sphero/. [Accessed: 27- Apr- 2015].

[3] Kaznov, Viktor, and Mattias Seeman, 'Outdoor navigation with a spherical amphibious robot.' Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on. IEEE, 2010.

[4] R. Chase and A. Pandya, 'A Review of Active Mechanical Driving Principles of Spherical Robots', Robotics, vol. 1, no. 1, pp. 3-23, 2012.