A proof of concept of self replicating robots for space settlements *

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Abstract. Efficient agriculture in a hazardous environment is an essential factor for space settlement. At the same time, transporting resources for settlement is very expensive and, to a certain extent, impracticable. It is therefore necessary to find techniques and tools to exploit resources on site. The aim of the project presented in this paper consisted in realizing a partially Self Replicating mobile Robot (SRR) that can monitor and helping to cultivate plants. The fibers of the plants have been used to build the frame of another SRR. This way, except for the electronic components, it was possible to replicate the robot through cultivated plants. In particular, it was possible to replace the weight of the new robot of 30%.

Keywords: Responsible consumption and production · Robotics · Space settlement · Plants in space · Self Replication.

1 Introduction

Ever since the dawn of the Space Age, humans have made plans for exploring and ultimately colonizing the surface of most planets and moons in the Solar System, with the main candidates by far being the Moon and Mars.

In most concepts for moon bases that have been put forward since the beginnings, the key role is that of life-support systems. If settlement and colonization is supposed to tend to complete autonomy from Earth, means to exploit resources *in situ* to provide breathable atmosphere, water, food and shelter are the main issue [10] [8]. Both for the Moon and Mars the soil and atmosphere (in the latter) in general provide all basic chemicals to support crops [14] [16] [10].

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In 2010, Maggi et al. in [7], produced a very thorough analysis of the influence of the martian environment on a possible agricultural endeavor.

Agriculture provides excellent sustainment capabilities to a putative planetary base. However, agriculture is also labor intensive, requiring multiple tasks to perform the basic activities. Providing a base with a single robot to perform all tasks is unrealistic; however, the costs associated with sending a fleet of robots from Earth are high. This is the main reason why the concept of In-Situ Resources Utilization (ISRU) is generally proposed [9].

The idea of employing growable materials to increase the potential of robotic systems or other functional structures has been investigated in literature [13]. The term "growable robotics" refers to a type of robotic systems that self-grow either a part or all with minimal input from external production infrastructure [11]. Ideally, following the fabrication of single components, the issue is that of assembling the parts in order either to perform maintenance, or to fabricate an entire robot [12].

Partial replication and assembly can be exploited also to the aim of "growing" the robot itself, or to enhance its capabilities [17].

Given the state-of-the-art of self-replication, assembly, "growing" etc. settlement and colonization activities can greatly benefit from this kind of technology domain. In particular, in 2002 Chirikjian et al. [2] and Ellery [5] propose the use of self-replicating robots to the development of the lunar surface; in particular Chirikjian analyzes the feasibility of SRRs in the context of lunar resource development. In [3], growing robots are introduced, starting from the original concept of a self-replicating automaton to the achievements obtained by plant inspiration, which provided an alternative solution to the challenges of creating robots with self-building capabilities. The use of 3D printing machines is considered enabling towards this endeavor, as Ellery points out in 2015 [4].

Building from the work presented up to this point, we propose a methodology and framework that enables self-replication through the use of agriculture as an ISRU technique. A mobile robot is sent to the target proto-planetary surface and is instructed to tend to crops (in our examples bamboo [1] [15]) which yield organic compounds like polymers and fibers, which in turn will constitute the structural components of the next generation of robots. This architecture is expected to completely automate the process.

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2 Self-replicating robot architecture

The main objective of the project is twofold. On the one hand, it consists in demonstrating that some structural components of a robot can be made out of vegetable fibres. On the other hand, it consists in demonstrating that the robotic system is able to automate certain phases linked to the production process of the required crops . Together, the achievement of the two objectives represents a first step towards the self-generation of robotic systems. The main schema the project and the modules involved are sketched in Fig. 1.

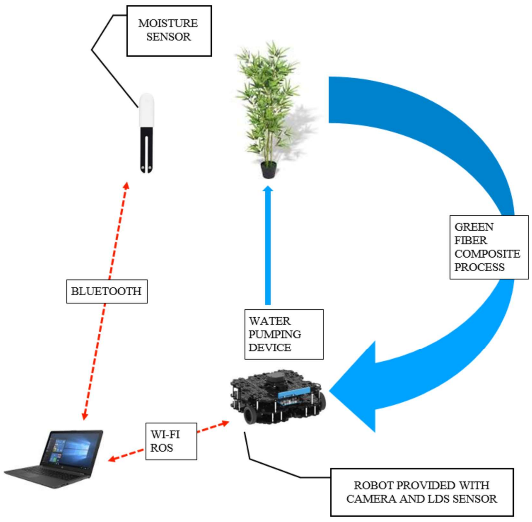

Fig. 1. Functional schematics of the project

A mobile robot has been employed to cultivate a plant of bamboo. There are several reasons why we decided to use bamboo. Bamboo is one of the fastest growing plants on the planet. A plant of bamboo can reach its full height in just one growing season and, over the next few years, the stem reaches maturity and hardness. Therefore the bamboo is highly sustainable since it can be harvested in few years. Moreover it possess interesting mechanical properties as far as compression and tensile strength [15]. For this reasons, it represents an excellent renewable and construction material [1, 6].

The robot and the plants are located inside an “arena” made of wood panels. The robot employed is a differential wheeled mobile platform, a TurtleBot 3[3]. The robot is provided with a camera (Raspberry pi camera) and a laser distance sensor (LDS). In addition, a water tank has been built. It is positioned above the LDS and allows, through the opening of a solenoid valve, to irrigate the plant

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[3] http://www.robotis.us/turtlebot-3/

when required. Inside the arena, a single bamboo plant has been rooted in a pot. To complete the system a sensor was inserted in the plant soil. It measures moisture levels and temperature. The research project is split in three phases. In the first one the robot cultivates the plant: by means of a vision system, considering also moisture data, it plans the irrigation of the plant and assesses its health condition. During the second phase, the plant is harvested and the fibres needed to make the composite material are obtained. The third phase consists in the realization of the structural components of the robot that are replaced to the original ones.

The robot first generates a 2D map of the environment by means of SLAM (Simultaneous Localization And Mapping) process, analyzing the data recorded by the LDS.

The robot receives instructions from a master PC through ROS (Robot Operating System). The master PC feeds the robot with actions, analyses the images provided by the camera and records data related to the plant soil conditions: moisture, temperature and light.

In order to cultivate the plant, periodically, the master PC performs the following tasks: a) Moves the robot to the target position (in front of the plant); b) Takes a picture of the plant; c) Performs the image analysis in order to derive plant life conditions (see next section for details); d) Measures moisture, temperature and light intensity (Bluetooth communication); e) If required, according point to c) and d), activates the irrigation system; f) Moves the robot to its home position. When the plant has fully completed its growth, its fibers can be used to produce the composite material.

3 Proof of Concept

In order to monitor the plants which have been assigned to its care, the main requirement of the robot is to be able to deliver water to the soil in the pot. Additionally, the robot must monitor the status of the plant, to insure its well-being and to signal possible drastic deviations. The plant watering process can be broken down in the following sequence of events: measurement of the water content in the soil and the status of the plant; loading of water from a fixed dispenser; navigation to the location of the pot; positioning of the water faucet on top of the pot; delivery of water to the soil.

3.1 Plant health monitoring: leaves color

The visual status of the plant is monitored via image analysis of the leaves. The robot operates in a structured environment in which the localization system is facilitated by the lack of additional obstacles and the vision system works with uniformly colored background surfaces on which the plants stand out clearly. At regular intervals, an image is taken of the plant and is analyzed. The element which provides a quantitative measure of the status of the plant is the color of the leaves. The image analysis process can be broken down as follows: localization

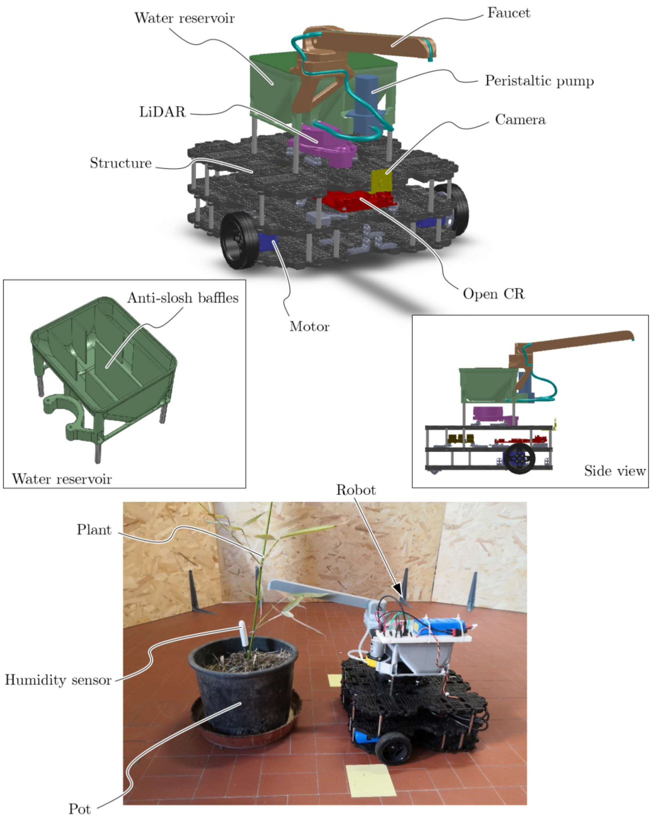

Fig. 2. Robotic system

of the pot; selection of the foliage Region Of Interest (ROI); recognition of the leaves and segmentation; auto-calibration of color data based on the segmented background; measurement of average leaves color in the segmented leaves data.

In Figure 3 the main stages of the analysis are visible; in a) the localization of the pot is visible. The localization is performed using a technique called cross-correlation, where a sample of the image (b)) is searched for in the base image. The position at which the pot is found by the algorithm is shown as a red crosshair in a) and is exploited to determine the ROI where the foliage is expected to be: this region is indicated by a red boundary in the same image. It should be noted that the size of the ROI is determined by the scale of the pot, which in turn is extrapolated from the cross-correlation results.

A second cross-correlation step is performed on the foliage ROI to determine the precise location of the leaves. The sample used in this case is much more complex: the baseline is shown in c), where one can see a set of single leaves; The result of this is shown in form of a map in d), which, using Otsu's thresholding technique, serves as the basis for the creation of a mask, shown in e). At this

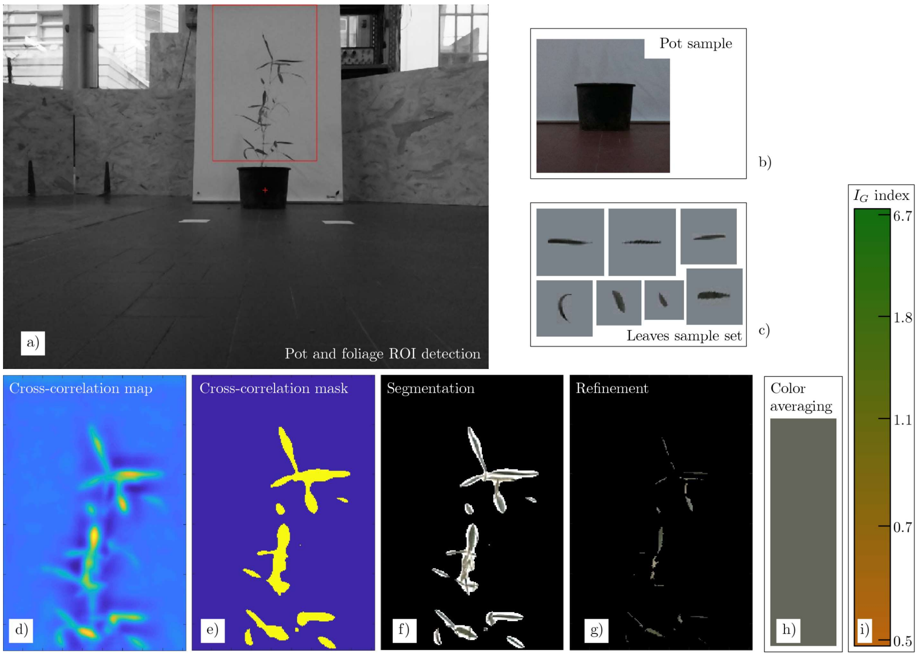

Fig. 3. Plant monitoring through image analysis. In a) the view of the camera is shown with the ROI highlighted in red (this view is shown in gray-scale here); in b) the sample for cross-correlation is shown; in c) the sample set is visible for the leaves detection; in d) through g) the main phases of the leaves detection are illustrated; in h) an example of resulting color is shown; in i) the scale of the index I_G is reported.

point segmentation is carried out and the approximate location of the leaves is determined; in order to completely remove the background, Otsu's thresholding is used again, thus refining the segmentation, as illustrated in g). Finally, the RGB data from this last masked image is averaged and the mean color of the leaves, extracted (h).

An index I_G is shown for each color, indicating how far the detected color is in the green spectrum compared to the other color components:

$$I_G = \frac{G}{R} \tag{1}$$

where G and R are the measured intensities of the green and red color channels in the detected color, respectively.

3.2 Bamboo fiber composite process

The goal of this sub-task was to define a manufacturing process for a polymer matrix bamboo fiber reinforced composite, suited to build the structural frame of the robots used for replacing some structural elements of the robot. This process requires human intervention because of its complexity and the many steps required.

Due to lack of time during the experiment, only one plant was grown. However, the process requires a large number of plants in order to obtain the necessary fibers. In our case, 3 trunks of plants were selected, each 1.5 m high.

In a first step, well seasoned bamboo stems were effectively crumbled in a general-purpose, two-shaft shredder. The resulting product was composed of a mixture of two prevailing fractions: internode fragments, characterized by a relatively high aspect ratio, and node fragments, characterized by an equiaxial shape. Since only the internodal fragments were considered as the suited fraction for further processing, a separation step is required. This was done using a dynamic flotation system, composed of a plastic tank, a water flow system and a collecting mesh filter (see Figure 4).

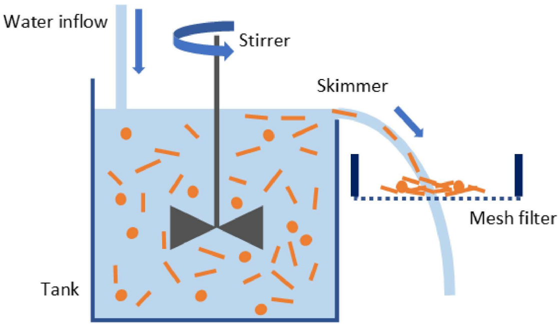

Fig. 4. Dynamic flotation system.

The useful fragments fraction was further processed, aiming to reduce the average fiber diameter, while preserving the fiber lenght (i.e. improving the fibers aspect ratio).

The resulting fiber mixture was then oven-dried, to reduce humidity to an acceptable level for incorporation into the resin matrix (60 °C, 24 h). Then, a square area of approximate dimensions 400x400 mm^2 was delimited with a vacuum sealing tape. The resin adduction tube and vacuum pulling tube were disposed along two opposite edge of the square. This area was then filled with a fiber layer, which was covered with a peel-ply tissue patch to avoid potential puncturing problems caused by the fibers against the vacuum bag (see Fig. 5).

The stack was then sealed with a polyethylene vacuum bag, and vacuum was pulled to check the air tightness of the whole system.

After 48 hours of curing at room temperature, the composite board was extracted from the manufacturing bed, and post-cured at 60 °C for 12 hours, to improve the mechanical properties of the resin matrix. The composite board was subsequently dry-sanded.

Fig. 5. Vacuum sealing process and the resin adduction device.

The mechanical properties of the composite have been determined with in-plane tensile tests, considering the material as quasi-isotropic in the board plane. The results of the tests show a value of the in-plane tensile strength of 25.6 ± 1.5 Mpa, with an initial elastic modulus of 4.9 ± 0.3 GPa. Eventually, the plate was cut to the required dimensions. It was used to replace the first structural layer of the initial robot, as it can be seen in Fig. 6.

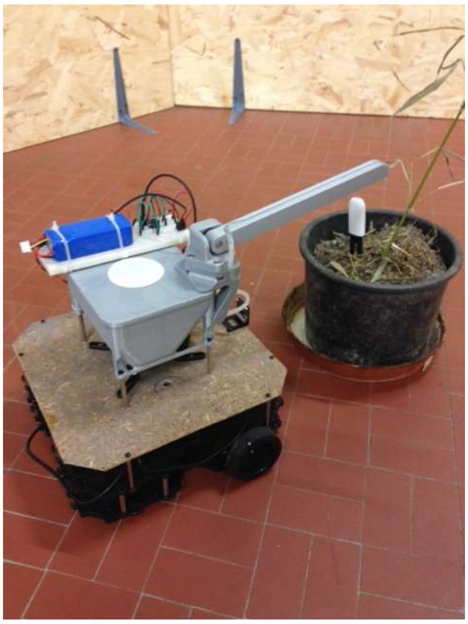

Fig. 6. Robot with the modified structure: one structural layer was replaced with the bamboo fiber one.

4 Conclusions

This project identified a roadmap to implement self-replicating robotic systems through the cultivation of plants. The principle that has guided this research is rooted in the extraordinary properties of plant fibers: low payload for space transportation, high mechanical properties, production flexibility and scalability. To validate the basic implementation strategy, a robotic prototype capable of growing bamboo plants has been realized.

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