An Integrated Power Aware System for Robotic-based Lunar Exploration

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Abstract—An integrated system for a power-aware robotic-centric exploratory lunar mission is the subject of this article. The robots communicate with a base station with a flexible protocol that can automatically change its attributes from multi to single hopping strategies according to the QoS of the entire network. The Base Station is responsible for the tracking of the robots and their re-charging. The robots’ re-charging is achieved via an optical-to-electrical energy procedure where a laser beam charges the photovoltaic cells attached at each robot. The experimental studies on a swarm of robots reveal the intricacies involved in a typical robotic-centric lunar exploration mission.

I. INTRODUCTION

Remote exploratory missions in human unfriendly environments, such as extra-terrestrial fields, utilize a group of robots despite the limitations thereby induced [1, 2]. Communication needs and autonomy issues arise, both in terms of energy and decision making.

The current work does not focus on the introduction of new ideas serving towards the optimal solution of the aforementioned difficulties, but rather offers the experimental validation – within the limits of a proof of concept experiment– of ideas already available in the field of aeronautics [3, 4]. Special care is taken in power consumption related issues, while emphasis is given in the remote robots’ re-charging process and the establishment of an at-all-times available communication link [5–7]. The scenario indicating the special needs of the mission is elaborated in Section II, while the components utilized are apposed in Section III. The results obtained from the experiment are provided in Section IV along with an elementary discussion. The paper summarizes in the last section.

II. PROBLEM STATEMENT

The scope of this work focuses in the development of a power-aware network and a swarm of mobile robots, whose mission is the exploration of the lunar surface. Optical–to–electrical energy conversion techniques are used to refresh the robots’ power supply, while the multi–hopping transmission policy is adopted to preserve the network’s reliability in a power–sensitive manner.

The robots’ re-charging abilities are available by equipping them with a set of photovoltaic cells for converting the optical energy produced by a laser beam. The mobile robots can communicate with a central unit—the Base Station (BaS), which is responsible for issuing supervisory control commands. The basic assumption for this experimental process is that among the laser system stationed at the BaS and the group of robots a Line of Sight (LoS) exists for the re-charging requirements.

The network constructed is a a Low-Rate Wireless Personal Area Network (LR-WPAN) with the objective to ensure the existence of reliable links among the BaS and the robots. Thus, the BaS monitors periodically the network’s status and decides whether, the transmission mode will adopt a multi–hopping policy or rather a single–hopping one. The multi–hopping transmission mode is considered as the response to an emergency situation for the current network and lasts until the link’s reliability is re–established.

Each robot, during its normal operation (i.e. the exploration procedure) monitors periodically its own power status. When its available power reaches a minimum threshold, an emergency signal is broadcasted by the robot, which transits in a standby mode; all mobilization related functionalities are sustained. When the BaS acknowledges the robot’s emergency signal, the latter re–obtains its mobility capabilities, while the BaS initiates the recharging procedure.

The recharging procedure consists of three basic phases; orientation, targeting and charging. The objective of the
orientation phase is to guide the robot in the proper position and orient it in such a manner that will ensure the alignment of the photovoltaic cells perpendicular to the laser system. The orientation phase terminates and the robot’s status re-enters at the standby mode. The second phase involves the guidance of the laser beam to the center of the photovoltaic cells’ set, based on a hybrid controller. When the laser beam has “locked” its position to the center of the photovoltaic cells’ set, the charging phase is activated, triggering the optical energy transmission. The charging phase, and consequently the recharging procedure, can be terminated by (a) the robot itself, when the termination criteria are satisfied, or (b) arbitrary by the BaS. Subsequently the recharged robot and the rest of the network return to their normal operation.

The basic phases of the power–aware mobile robot group are highlighted in Fig. 1, in which the robots explore the territory, while communicating with the Base Station either via single, or multi hopping (a, b). The circles indicate each node’s transmission range. Entering the charging procedure, (c), the robot notifies the rest of the network, while the Base Station initiates the orientation phase (d, e, f). The targeting procedure is terminated with the laser beam transfer (g). Note that the position of the laser system, residing at the Base Station, ensures the LOS among the laser beam and the robot. After the charging process the group continues its exploration (h, i, j).

III. COMPONENTS

A. Mobile Robots

The demands of an exploratory lunar mission in a distant, unknown and unfriendly environment vary and necessitate the formation of a group of robots with a respective variety in capabilities. In terms of mobility the “skill” variation is incorporated to the current scheme via the use of both wheeled and legged robots manufactured by Lynxmotion [8].

A hexapod named Arachne, is the team’s scout–leader and is equipped with both communication and re-charging devices. The legged robot incorporates 18DOF (3 per each leg) and the mobilization patterns may significantly vary, depending on the selected inverse kinematics scenario, via the adjustable parameters of the gait height, the clear distance from the ground, the speed and the ability to instantly change the movement’s direction.

Similar convenient mobility patterns posses the wheeled robot followers of the team. The team followers are 4 wheel-driven robots, differentially steered, while their chassis articulation provides an additional DOF, which gives them the ability to overcome comparable to their own size obstacles.

The basic configuration of the mobile robots has been enhanced to include RF–attributes. The robot’s wireless motion control requires their integration with radio–capable components, such as the TELOS platform [9]. The robot–TELOS interconnection is realized at the physical level, where home–made electronics have been developed to allow for the proper signal exchange and the monitoring of specific power related parameters.

The robot’s autonomy, in terms of power, is provided by Li–Ion battery packs, whose voltage and current drawn are monitored and can trigger the charging process.

1) Arachne’s Modifications: In addition to the TELOS, the Arachne is equipped with customized solar cells necessary for the recharging procedure by the laser beam. The three components (Arachne, TELOS and power supply system) are interconnected through a supervisor unit, as shown in Fig. 3. The supervisor circuit monitors the battery status and the TELOS-Arachne communication.

The supervisor unit is based on a AVR ATmega8L micro–processor board. Its main task is to monitor the battery status, by reading the battery voltage and the current drawn by Arachne. Measurements of both voltage and current are necessary to obtain a reliable estimation of the remaining charge in the batteries.

In normal operation with charged batteries the supervisor unit allows the communication between TELOS and Arachne, and consequently between the BaS. In the meanwhile the supervisor unit monitors the voltage and the current of the batteries and determines the status of the batteries. If the remaining charge reaches a minimum threshold, the supervisor unit alerts the Arachne and shuts it down. A “Need Charge Signal” is broadcasted via the TELOS periodically until a reply from the BaS is received. The Arachne is enabled again and the BaS guides it in order to align its solar cells with the laser beam in the desired orientation. When the BaS determines, that the laser has targeted the solar cells, Arachne is disabled again to minimize power consumption and to proceed with its charging procedure.
The charging algorithm incorporates temperature \((\Delta T)\) termination criteria. The choice of the temperature as a charge-termination meets two objectives. First of all, it allows for fully battery charging, without overcharging risks. Secondly, the power supplied by the solar cells varies greatly depending on the operating conditions, and therefore, it is impossible to maintain a constant charging voltage or current when considering photovoltaic systems. Thus the choice of the voltage termination criteria is excluded. After the charging termination criterion is met the supervisor unit (Section III-A) informs the BaS for the completion of the charging and enables Arachne.

2) Idmon-Athena: The Idmon’s motor controller was programmed to accept serial commands by the TELOS platform. The four DC motors of the robot followers are driven by two full-bridges operated by the PWM signals issued by its basic \(\mu\)-controller. This configuration allows for full control of the robot’s speed and speed inversion, while minimizing the power losses.

B. Network Transceivers and Architecture

The robots are organized via a semi–centralized collaboration scheme. The goal of this scheme is the remote motion control of the set of robots and the ability of the BaS to recharge them. The only locally-made decisions on the mobile-robots’ side are related to the broadcast of an alert-signal indicating that the robot needs to be recharged. The reliable communication among the robots and the BaS calls for a hierarchical network topology; the network constructed is consisted of three types of nodes. 1) The BaS is the primary intelligent node that provides the majority of the network’s decisions and synchronizes the messages received/transmitted from/to the latter’s members. 2) The mobile robot–nodes need to recognize the message–ID and provide the appropriate handshaking to the robot’s controller. 3) The least intelligent nodes are the stationary ones, used primarily for data broadcasting.

Another level of the network’s hierarchical topology appears at the transmission power level each node operates, according to its power supplies; the BaS, which is always plugged in, may operate at the highest power level possible. On the contrary, the robot–nodes adopt an energy–conservative policy for their communication with the rest of the network. Finally, the stationary nodes, whose power consumption is limited only to the transmission power, operate at a higher transmission power level than the robots, but still in an energy–efficient manner.

The network deployed relies on the wireless 802.15.4 platform [10], implemented via the TELOS units. An instance of the network setup is depicted in Fig. 4.

The constructed network operates in a power–sensitive manner, while simultaneously ensuring the connectivity among the operational nodes. For the purposes of our experiment this is translated into the existence of a –at all times– reliable, multi–hop path, from the BaS, to the robots–units. Consequently, the adopted networking policy aims at minimizing the possibility of failure during the data exchange over the wireless link. The linkage breakdown between two IEEE 802.15.4 nodes, caused by network-related conditions, is subject to the following conditions: a) the transmission range of the operational nodes, and/or b) their antenna relative orientation, as a result of the radio irregularity, a phenomenon described in [11, 12]. The latter means the existence of “blindfold” regions that may affect substantially the network’s performance.

The utilized network performance metrics are: (i) the packet loss ratio \((\lambda)\), and (ii) the Received Signal Strength Indicator (RSSI). The packet loss ratio is defined as the ratio of the replies received \((N_{RX})\) from the BaS to the Arachne to the number of corresponding commands transmitted \((N_{TX})\). The RSSI is a measurement (in dBm) of the signal’s strength. For the IEEE 802.15.4/TELOS case, typical values of the RSSI vary from 0 to -54 dBm.

The implemented algorithm is a polling-oriented procedure deciding about the packets transmission mode. The BaS periodically transmits a beacon–request destinating Arachne. From the Arachne’s reply (beacon–acknowledgment) the BaS records the minimum value of the RSSI received, and updates the number of beacon–acknowledgment transmitted. If no beacon–acknowledgment arrives at the BaS, then the packet is considered lost. The RSSI measurement is set to -54dBm, while the lost beacon–acknowledgment counter increases by 1. When the number of the beacon–requests reaches a user-defined upper limit the present batch period is over.

The packet loss ratio and the mean value of the RSSI measurement recorded are calculated. If the results are within certain preset limits, then during the next batch period the transmission mode is set to single–hop. Elsewhere, the transmission mode switches to multi–hop; the BaS broadcasts the packets destinating to the Arachne and the stationary nodes become the data forwarders, between the BaS and the Arachne.

C. Mobile–Robot Visual Tracking System and Laser–based Charging

The mobilization and intercommunication tasks performed by each robot are achieved through the use of the aforementioned components and can cover the team’s needs while maintaining the “proper operation” conditions. Transiting on the “charging operation” though, additional information, such as location and orientation of the robot, is needed which is not available by any of the previous tasks. Furthermore, the recharging scenario incorporates the use of a high energy laser beam pointing at the block of photovoltaic cells carried by each robot. The intrinsically non-safe nature of the targeting process requires accurate positioning of the laser spot on the block of the photovoltaic cells. These reveal the necessity of closing the control loop, results in the incorporation of the visual servoing system.
A digital camera (SONY HANDYCAM PC-1000E) grabs the required sequence of frames at a frequency of 25 frames/sec and feeds it in S-Video format to an IMAQ hardware unit manufactured by National Instruments (PCI-1411) [13]. The laser diode and the collimation optics reside on a Pan Tilt Unit (PTU), provided by Directed Perception (D46-70) [14]. The pan and tilt movements of the current PTU are performed in steps of 0.012857°. Depending on the distance of the target to the camera, the camera lens’ noise error is set (i.e. 2 pixels) at a 10 m distance.

The targeting procedure followed in the current work, is split into two steps. Firstly, the robot in need of charge is required to orient itself - facing the BaS, under the instructions and the visual supervision of the latter. Secondly, the collimation tube (hosting the power laser) is guided via the closed loop controller on the target (robot’s photovoltaic cells), whose location has been extracted in the previous step of orientation.

1) **Orientation**: The location of the mobile robot and the target (block of photovoltaic cells) is identified via the use of two blinking LEDs positioned sideways of the photovoltaic block. The two LEDs blink at a matching frequency with the grabbing frequency of the monitoring camera, so that at each grabbed frame only one LED is visible (ON). Each pair of subsequent frames is subtracted, during this process, allowing for the elimination of the redundant information. Following the identification of the two LEDs, the Euclidean distance between them is calculated (the target is located at the midpoint) and the goal is to maximize this variable. For this reason a simple but rather efficient strategy is followed: the robot performs two movements, a) a full rotation is performed which allows for the construction of a look-up table, and b) the robot is ordered to rotate until the maximum value of the look-up table is assumed for the second time using a simple hill-climbing technique. The final step of the orientation algorithm is to transmit the “Power OFF” signal to the robot’s supervisory unit and to pass over the identified target’s pixel coordinates to the targeting algorithm.

2) **Laser Targeting Algorithm (LTA)**: A straightforward utilization of the power laser beam is prohibited due to increased danger to the equipment. Thus, a low power laser spot is utilized, until the control specifications are fulfilled from the control scheme (error bellow a predefined threshold). The current algorithm realizes a simple hybrid P-controller, which aims in minimizing the error signal produced as the difference between the laser spot’s position and the target’s coordinates obtained as output from the orientation algorithm. The laser spot is identified via pattern matching techniques [15,16], within a specific Region of Interest (ROI). The errors produced by noise infiltration are minimized by applying the pattern matching algorithm within only a prescribed ROI, which is a bounded region within the camera grabbed frame moving in accordance to the dynamics of the PTU. The hybrid nature of the controller results from the failure of the pattern matching algorithm to identify a laser spot match within the frame. An additional state is thus considered which toggles the output of the controller (ON-OFF) and resets the control signal. The robustness of the controller is enhanced through the use of a moving average filter applied on the laser spot coordinates located in the frame.

**D. Laser Illumination System**

The primary component of the utilized laser system is its laser diode; the main reason for choosing a laser diode instead of other system configurations (e.g. CO2, He-Ne) is the demand for continuous wave emission of laser with high power output at a reasonable cost. These demands are satisfied by laser diodes emitting in the near IR region, despite the fact that the produced radiation pattern needs collimation optics. The laser diode utilized was manufactured by High Power Devices (HPD) [17], providing a maximum of 5 Watts continuous output power.

For the development of the laser system, custom electronics were designed. The operation of the laser diode at a specified power level requires constant current at a specified temperature, since the output power of the laser diode is highly dependent to the junction’s temperature. A temperature controller is implemented to absorb the heat losses produced by the laser diode and keep the temperature constant, independent of the output power level and the ambient temperature. The laser diode calibration characteristic, as shown in Fig. 5, were provided by the manufacturer at 25°C. The controller’s temperature set-point was set at this temperature in order to allow for a reasonable estimation of the output power by measuring the diode’s current.

![Laser Diode Characteristic curve](image)

**Fig. 5.** Laser Diode Characteristic curve [17].

The need to converge the laser beam at the target was covered by the use of collimation optics adjusted so as to produce a properly aligned beam at a distance of approximately 10m. The collimation optics were provided by Thorlabs [18]. In Fig. 6 the closeup of the power laser with its cooling system, the collimation optics and the low power laser, residing on the PTU is highlighted.

![Closeup of the power laser with its cooling system, the collimation optics and the low power laser, residing on the PTU](image)

**Fig. 6.** Closeup of the power laser with its cooling system, the collimation optics and the low power laser, residing on the PTU.
E. Photovoltaic Cells

The power–charging of the lunar-ROVERs can be obtained via optical-to-electrical conversion [19] and specifically via laser-based targeting of photovoltaic cells.

For the purposes of this application, solar cells with a maximum efficiency in the wavelength region of 808nm were selected; this selection was made due to the operation conditions of the laser beam targeting them converting the optical to electrical energy. The utilized polycrystalline silicon solar cells have $37 \times 66 \text{ mm}^2$ active surface and are rated 6.7 V at 30mA. The cells are mounted on a fiberglass substrate and have a tough epoxy sealant on top. Multiple cells can be wired in parallel for higher current applications. The charging is stopped by the supervisor unit, (Section III-A) by voltage and temperature criteria.

IV. EXPERIMENTAL RESULTS

The overall integrated system was tested in laboratory–conditions. The area for the “hypothetical” lunar system was $60 \text{ m}^2$ $(15 \times 4)$.

In the network constructed, besides the BaS the two mobile robots (Arachne and Idmon) were involved and three stationary nodes for the realization of the switching transmission mode algorithm. The network’s efficiency measured by the aforementioned metrics III-B, was tested for a smaller scale network consisted by the BaS, the Arachne and (a) zero, (b) one, or (c) two stationary intermediate nodes. The RSSI value recorded for each case (a, b, or c) is outlined in Fig. 7. Note that Arachne’s antenna operates at the minimum transmission power level possible (-25 dBm), while the BaS’s antenna operates at the maximum transmission power level (0 dBm). The antenna’s operation at different power levels results in different transmission range for the nodes involved in the link. The measured RSSI values presented at Fig. 7, highlight the repetitious failure of the direct link. There exist two possible explanations for the recorded failure; (a) the Arachne cannot receive the commands transmitted by the BaS because the former does not belong to the latter’s transmission range and (b) even when Arachne successfully receives the BaS’s commands, its acknowledgment messages are too “weak” to reach directly the BaS. The entrance of a stationary node that can re-broadcast the exchanged packets improves the network performance; the link becomes “stronger”, while the packet loss ratio reduces from 100% to 62%. The efficiency of the switching transmission mode algorithm is even more evident as the small–scale network is integrated with the second intermediate node; the mean RSSI value recorded increases from -51dBm (1 intermediate node) to -47 dBm, while the packet loss ratio is limited to 30%. The aforementioned experimental results prove the necessity for the presence of intermediate nodes so that safe communications conditions, are constantly present. This safe-operational strategy is also adopted during the “charging phase”. When the alert signal reaches the BaS, the network switches on to the multi–hoping scheme, in order to minimize the low QoS for this critical procedure. Several runs took place to experiment with the remote navigation capabilities from the BaS to the robots for exploring the “unknown” territory, while a pair of beacons (stationary nodes) is placed in “high ground”. This case is depicted in Fig. 8a, while the orientation procedure is provided in the three sequel frames (b, c and d). Arachne has transmitted the “Need Charge” signal and its position is being identified by the BaS via the rotation-procedure and the pair of blinking LEDs. In the mean time, Idmon does not interrupt its “normal operation” tasks, unless needed. As soon as Arachne is aligned with the laser tube, the robot’s power is switched off (excluding its supervisory unit) and remains in this mode awaiting for the charging (Fig. 8d).

![Fig. 7. The RSSI value recorded for (a) 0 intermediate nodes, (b) 1 intermediate node and (c) 2 intermediate nodes.](image)

The targeting algorithm is robust enough to perform within the accepted limits (Section III-C), despite the induced noise. Fig. 9 provides the laser spot trajectory obtained at three iterations of the experiment. The initial horizontal movement of the laser spot is due to the lag in the activation of the one input of the Two Input Two Output (TITO) controller. Visual representation of the results may be found at the two bottom left frames of Fig. 8(e, f). Although the power laser beam operates in the IR spectrum, it remains visible by the camera lens and is shown in Fig. 8g. The set of photovoltaic cells residing on the Arachne consists of three cells, coupled in parallel. The maximum electrical power obtained for this
topology is highlighted in Table I.

It is evident that the large beam diameter – compared to the width of the block of the photovoltaic cells– results in energy loss and can only be compensated by the increase of the photovoltaic block’s surface, or by the collimation of the beam at a more spot-like shape. An issue of concern is related to the exploitation of the entire optical energy by the cells (at different distances from the source), which demands the incorporation of an adaptive collimation scheme–utilizing a controllable collimation lens.

The last of the group of 8 frames of Fig. 8(h), reveals the self-efficacy of the power autonomous group, which may carry out its exploration tasks, without the need to return to the Base.

V. CONCLUSIONS

The experimental study here presented, reveals the feasibility of formulating and remotely controlling a power–aware system. A proof–of–concept experiment, though utilizing mainly commercially available hardware and equipment, proves the efficiency of the suggested scheme in terrestrial environment.

Issues for the optimization of the implemented power–aware network involve several of the components described above. The mobile robots’ “intelligence” can be enhanced by integrating their functionalities with more advanced exploratory capabilities. For instance, regional mapping techniques, advanced sensory systems for extra–terrestrial environment. Mapping of the explored territory can be easier achieved by exploiting more efficiently the available visual means, as by tracking the group of robots position and when asked upon zooming in and focusing on the “critical” area, as, for example, a robot in need of charge. Finally, an adaptive collimation–optics system may be utilized in order to achieve better concentration of the laser beam at various distances from the target.

<table>
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<tr>
<th>Laser Output Power</th>
<th>Short Circuit Current</th>
<th>Open Circuit Voltage</th>
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<tr>
<td>5W</td>
<td>111mA</td>
<td>7.8V</td>
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### Table I

The maximum electrical power obtained by the Arachne’s set of photovoltaic cells

**REFERENCES**


