A wireless recharging system for electrical agriculture robots with autonomous docking

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Abstract. In this work we present a system for the autonomous recharge of the batteries of an electric powered mobile robot, developed in the context of agricultural robotics. The system is composed of a wireless charging station at high power which can provide up to 4 kW and an autonomous docking algorithm exploiting a camera and a laser range finder.

The wireless charging station consists of a power supply and two coils for the wireless power transfer, one attached to the docking station and one attached at the bottom of the robot. Since a mechanical plug is not used to establish the electrical connection a high precision alignment docking is not required. However, the better the two coils are aligned, the more power is transferred and the efficiency of the recharging system increases. The robot navigation module is based on the standard navigation stack of Robot Operating System (ROS). This is used to get close to the docking station, while a fine grain motion planner was specifically developed for the docking task. It generates a precise alignment of the robot's coil with the ground coil by fusing the sensory information from the camera and the laser range finder.

A detailed description of the wireless charging station and of the motion planner is reported together experiments on a real robot showing the good performances of the complete system.

Keywords: Wireless charging, docking station, mobile robots, motion planners, alignment

1 Introduction

This work is part of the *DODICH* project (the website is at *www.ethics.it/dodich*) co-financed at local level by the EAFRD-European Agricultural Fund for Rural Development of Veneto Region. The project's aim is to develop an autonomous robot that is capable to perform simple operations in the vineyards, like spraying chemicals, without the human intervention.

The agricultural sustainability problem becomes every day bigger. The population growth, which leads to an increasing demand of food and the global awareness of the hazards due to chemicals, are pushing the way for precision agriculture.

With the recent advances of the state-of-the-art, agricultural robotics is becoming a big deal both for economic and for health reasons. Pushing away farmers from the spraying tractors and reducing the quantity of emitted chemicals (and the relative costs) with intelligent crop treatments are only two of the plethora of reasons that form such big deal.

The majority of mobile robots used in research laboratories are powered by battery packs that power electric motors. To make such robot cost-effective to be used in production lands they should be able to work 24h a day, every day. For this reason the research of new methods to refill or recharge such robots is crucial.

In this work we propose a wireless charging and docking system. The main reason for wireless is that the exposition in outdoor environments can cause damage to mechanical connectors (oxidation, dirt, etc.). Since the power that is necessary to transmit to charge the robot batteries can be very high, if the connectors are not well coupled, dispersions and even some dangerous situations can take place.

2 Related Work

For this work we used the Pioneer 3AT in Fig. 1a suited with an Hokuyo URG laser-scanner and an ASUS Xtion PRO LIVE. Currently there are many other companies that sell outdoor mobile robots. Nevertheless the number of custom outdoor robots that are in use in research labs is very large. Just to mention some the Quadrivio from Politecnico di Milano [1] or the Armadillo from the Frobomind project [2]. This to say that the user-base of a wireless charging solution for outdoor mobile robots is potentially quite large.

Since some years there has been successful attempts to the docking problem. The first was the one by Grey Walter [3] in 1953 with a light following behaviour. Other and more recent vision based attempt has been made by Cassinis et al. [4] in 2005 with a work inspired by a nautical approach with range lights. Or the one from Low et al. [5] in 2007 in which they got the inspiration by honey bees and they proposed a behavioural control law based on optical flow estimation. The optical flow estimation approach was previously followed also by Santos-Victor et al. [6] in 1997.

Another solution proposed was with infra-red emitters and detectors, as example the one from Hada and Yuta in 1999 [7] or more recently in the work by Song and colleagues [8].

In the presented work we use a datamatrix tag attached over the docking station. It has the advantage to easily give the full 6D pose of the docking station while it is visible by the camera. With this information, the robot can easily localize itself in respect to the docking station and a precise control law can be applied to the robot to perform the docking. The usage of a QRcode or other similar kind of tags is not a new approach to the localization problem. In 2013 McCann et al. in [9] used tags to augment the environment, storing in the landmarks informations like their 3D position. A similar approach with a different kind of tags were presented in the work by Bergamasco et al. [10] in which they proposed a particular kind of tags that offers a robust detection with high precision.

3 The Proposed Solution

The robot used for this work was the Pioneer 3AT Fig. 1a. In Fig. 1b is depicted a scheme of the charging system. There is a generator (Fig. 1a left) attached to the wall plug that supply the field coil. The robot mounts the pick-up coil at its bottom (Fig. 1a right), that it is attached to a rectifying circuit that supply the on-board battery charger.

The robot is equipped with an on-board laptop, connected via a serial interface to the low level robot controller (which deals with motors, encoders, etc.). The sensors (the ASUS Xtion and the laser-scanner) are connected via an USB cable to the on-board laptop. The robot is controlled with ROS.

The ROS core and the navigation planners are launched in a separate computer. The two computers are connected together with a WIFI network. The desktop computer send standard ROS navigation commands to the on-board laptop which executes them on the robot. Vice-versa, the on-board laptop send sensors data to the other one enabling it to perform robot localization and mapping of the environment.

The proposed solution is divided in two main parts: the electrical wireless charging system will be discussed in section 3.1; whereas the docking algorithm in section 3.2. An experimental evaluation is discussed in section 4.



Fig. 1: The system set-up: in Fig. (a) the robot; in Fig. (b) the overall system scheme.

3.1 The Wireless Charging System

Nowadays, the increasing use of electric vehicles leads to the need for a technique to wirelessly charge these applications: wireless power provides a safe way of charging that can be used in an automatic system, being the not simple and disadvantageous process of plugging the power cord into the socket unnecessary.

As the charging system is often fully embedded, wireless charging can be realized in waterproof packages and so wireless charging is attractive in situations at which rechargeable devices need to be frequently used near water as well as in humid conditions.

Compared with plug and socket charging, the primary advantage of the wireless charging approach is that the system can work with no exposed conductors, no interlocks and no connectors, allowing the system to work with far lower risk of electric shock hazards and, avoiding bad contacts between plug and socket, preventing also fire hazard.

The easiest charging system that can be used is based on induction theory: as shown in Fig. 1b, the wireless power transfer system involves two coils of the same dimension with a high frequency power source: the power is transmitted thanks to the magnetic coupling between the two coils (that act as a transformer) and then rectified and used to charge the batteries of the vehicle.

Similar approach can be found in state-of-the-art works like the one of Naik et al. [15].

Both field and pick-up coils consist in 25 turn made by Litz wires and have respectively at the bottom and upper face a ferrite core fixed on an aluminium disc in order to reduce the leakage of magnetic field: as it can be noted, the typical pancake winding has been used thus allowing a good matching of the system even if the coils are not perfectly aligned.

The experimental set-up consists in a 100 kHz and 4 kW generator and a very simple half way rectifying circuit (one C-Si diode and one 0.47 F capacitor) able to feed a typical charger (12 V, 2.5 A) connected to the three batteries of the robot.

Compared to direct contact charging, inductive charging efficiency is lower and resistive heating is higher; moreover, due to the large air gap between the primary and secondary windings, contact-less transformers have large leakage inductances, small mutual inductance and low efficiency. However, it's important to highlight that this system was not explicitly designed for this application and the aim of the experiment is only a demonstration of the feasibility of an automatic charging; anyway it can be easily demonstrated that it's possible to increase the efficiency of the system by means of proper designed magnetic core, a good choice of rated frequency and, when it's possible, reducing the air gap.

3.2 The Docking Algorithm

A map of the environment is created using laser scan data with the GMapping algorithm from Grisetti et al. [11] that is provided by ROS. The system work on the created map.

We distributed the ROS nodes in part on the on-board computer and in part on a desktop PC, used to easily monitor the operations and which will be referred as the monitor computer. In particular the on-board computer runs the robot and sensors drivers. The monitor computer instead runs the core node, the planning algorithms and the visualization tools.

The docking algorithm is divided in three parts: (a) the ROS navigation stack; (b) a motion planner for the docking station's approach; (c) a bearing correction component.

The first phase is performed with the standard ROS navigation stack. It is used to reach a position in front of the docking station. To achieve that, the user sets the goal position in the map with the RViz ROS visualization tool. The robot localize itself in the map with the Adaptive Monte Carlo Localization (AMCL) algorithm, described by Fox in [12], that is implemented in a ROS package as part of the navigation stack. When a path is computed, the monitor computer send a series of velocity commands that navigates the robot to the goal position.

A tailored motion planner starts when the datamatrix tag attached over the docking station become visible by the camera (see Fig. 2). The maximum distance that the datamatrix is robustly visible depends on: the marker size, the camera resolution, the point of view and on ambient light condition. With the used robot set-up and a marker edge of 17 cm, the marker is visible until a distance of 2.5m.

The planner is based on the work of Park et al. [13] in which they presented a smooth control law for differential drive robots as the one that we used. With its control parameters the control law can be easily tuned to let the robot make a graceful curve to reach as best as it can the final goal position and the desired orientation.

We chose this motion planner for the simplicity to obtain a graceful curve and because it uses egocentric polar coordinates with respect to an observer on the robot. The egocentric coordinates are far more intuitive when a robot is tracking its target position and direction.

With its control parameters it is quite easy to set a smooth trajectory that keeps the datamatrix visible.

The datamatrix is physically attached to a wall, its pose is computed by a ROS node using the calibrated RGB camera on the ASUS Xtion sensor. With the laser scanner the wall parameters are computed with the Hough transform algorithm by Matas et al. [14] implemented in the OpenCV library. The two types information are fused, giving more relevance on the laser-scanner data. The fusion has two steps: (a) we project the point of the datamatrix pose and the extracted line on a ground plane to obtain a local 2D map and (b) we move the datamatrix center on its orthogonal projection on the scanned wall's line.

The field coil is $50 \, cm$ in front of the wall aligned with the datamatrix center, a target point for the motion planner is set on it. Since the field coil is circularly shaped (see Fig. 2), the robot can approach it from every direction. For this reason, when the robot is very near (this distance is a parameter) to the field coil only the robot's bearing has to be adjusted. This is very easy using the egocentric polar coordinates, that the Park's control law needs [13], of the target in respect to the robot's center. The goal of this step is to reach a very small angle between the robot's bearing direction and the robot-target direction.

Then the robot need only to go straight for the last few centimetres to get over the coil.



Fig. 2: The overall system configuration used in the experiments

4 Results

The overall efficiency of the charging system depends on the power transferred to the load (in this case the batteries of the robot). In particular, when transferring 35 W, the absorbed power is 80 W (43% efficiency), whereas when transferring 78 W, the absorbed power is 125 W (62% efficiency). Anyway, it must be noted that the generator, being designed for a 4 kW maximum power, has a no-load consumption of 43 W, thus the previous measurements shows us that the efficiency of the coil system is in both cases 94% as also reported from the work of Bertoluzzo et al. [15]. When the coils are not on the same axis, there's a loss of efficiency: i.e., with 2 cm off, the loss is about 5%.

To evaluate the docking algorithm we modified the robot by adding a fixed structure over it to attach more precisely the sensors (see Fig. 3a). Due to this modification we moved the target position $76 \, cm$ in front of the wall to avoid collisions with the Hokuyo.

A top-view of the conducted test is depicted in Fig. 4. We put the robot in 10 different starting poses (manually measured). To evaluate the robot's final pose error, we manually measured the segments depicted in Fig. 3b. The segment \overline{PA}

is the distance between the coil center and the robot's final direction, \overline{CP} is the distance between the robot's center and the coil center orthogonal projection on the robot's final direction and \overline{CA} is the distance between the robot's center and the coil's center (computed). The results are in Tab. 1.

Test $\#$	$\overline{PA} \ (mm)$	$\overline{CP}~(mm)$	$\overline{CA}\ (mm)$
1	4	9	9.85
2	2	2	2.83
3	3	6	6.71
4	9	13	15.81
5	3	10	10.44
6	2	4	4.47
7	7	3	7.62
8	1	1	1.41
9	2	6	6.32
10	5	3	5.83
Table 1. Test results (see Fig. 3b)			

The results shows the ability of the docking algorithm to approach the target pose with a reasonable error. The alignment error is always under 2 cm.



Fig. 3: The docking evaluation test: Fig. (a) shows the robot's set-up used for the docking evaluation; Fig. (b) depicts the measured segments (\overline{PA} , \overline{CP} and \overline{CA}); Fig. (c) shows the robot recharging (the multimeter shows the output of the battery charger mounted inside the robot that is recharging the robot's batteries and that is powered by the wireless charging system).

In Fig. 3c it is visible that the robot can recharge its batteries. The displayed number on the multimeter is the voltage measured at the output of a battery charger mounted inside the robot that is powered by the wireless charging system and that is connected to the robot's batteries.



Fig. 4: The top-view of the docking evaluation

The system, in the proposed set-up, is capable to perform a recharge of the batteries every time that the robot gets, with its body, over the field coil. Even with misalignment of a few centimetres of the coil, enough power is transferred to supply the battery charger.

5 Conclusion

This work provides a demonstration of the feasibility of a simple wireless charging system that is able to recharge electric actuated mobile robots. The outdoor environments in where agricultural robots work can be dirty and quite challenging for a very precise and safe docking. The system is robust to even large errors in the docking.

Moreover, by means of a communication system between the generator and the rectifying circuit, it's possible to drive the robot so that the coils can be aligned on the same axis with a good accuracy: in particular, the controlling system can drive the robot by means of a measurement of the impedance detected by the generator (proportional to the alignments of the coils) or by a the measurement of the induced voltage on the pick-up coil, using in both cases a very low power input. With such a feedback system, from Tab. 1, one can expect to reduce the alignment error under 1 cm.

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