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Design and implementation of autonomous wireless charging station for rotary-wing UAVs

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Rotary-wing UAVs such as multicopters have the ability to operate in confined spaces, to perform high maneuverable motions, and to hover at a given point in space and perch or land on a flat surface. This makes a multicopter a very attractive aerial platform giving rise to a myriad of research opportunities. Yet, these opportunities are often severely limited by the constraints on the multicopter's flight time due to its limited battery capacity. This in turn results in the limits on the payload of the multicopter. Fortunately, by introducing a team of autonomous multiple multicopters running an automatic and wireless battery recharging process without any human intervention, the overall mission time can be greatly increased and subsequently relax the constraints on the flight time and the payload. As a first step towards this idea, a cheap charging solution using wireless power transfer (WPT) is proposed for a single multicopter in this paper. It turns out that the proposed solution achieves a power transfer efficiency of greater than 50% on average (reasonable compared to the existing similar solutions). Also for a demonstration of the proposed recharging solution, an interface between an open-source flight controller and a ground PC is also uniquely designed and implemented to successfully allow for autonomous position control and navigation in an environment equipped with precise vision sensors (VICON cameras).
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1. Introduction

Over the last few years, the usage and deployment of UAVs (Unmanned Aerial Vehicles) have been growing, from hobby to military applications. Some of those applications include surveying, maintenance and surveillance tasks, transportation and manipulation, and search & rescue [1,2]. In particular, a great deal of attention has been paid to rotary-wing UAVs (also known as drones). Fig. 1.1 shows a typical rotary-wing UAV termed as 'multicopter'.

A multicopter is a multirotor-propelled UAV which has high mobility and kinesis. The lift and thrust is generated by the propellers mounted on high-speed, high-power brushless DC motors. Multicopters use an electronic control system and electronic sensors to stabilize themselves. With their small-size, agile maneuverability and VTOL (Vertical Take-Off and Landing) capability, multicopters can be flown indoors as well as outdoors. Similar to a conventional helicopter, multicopters can hover but have significant other advantages such as ease of piloting and mechanical simplicity. In recent times there has been an explosive growth of interest in multicopters spurred by the availability of research-grade platforms and motion capture systems such as VICON [3,4]. However, the most significant constraint on any aerial vehicle for persistent missions is the depletion of its on-board power resource. Due to high current requirements of the motors, the flight time of a multicopter is highly limited which prohibits long-time operations. The energy needed to perform the flight is stored in a battery, which is often heavy and therefore limits the flight time of the multicopter. Even with a fully charged battery in a controlled environment, the multicopter is able to fly for only a few minutes. If it carries some other weight such as a camera or a kind of measurement device, the flight time will be further reduced. Thus, there is the obvious need to charge the multicopter's battery of-

Fig. 1.1. Multicopter with four rotors.

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ten for a long-time operation. Unfortunately, this charging job has been done through direct human intervention, which motivates a design of the automatic procedure of making the multicopter land on a charging station, charges, and resumes the mission without the constant need of human intervention.

The concept of refueling (charging) a UAV during a mission has been around to help to prolong the flight time and to provide the ability for longer missions [5,6]. At the University of Southern California, researchers have demonstrated a ground robot that has the ability of autonomous recharging on a stationary "charging dock" and resuming its original task [7]. Along a similar line, another group has been working towards implementing a battery swapping station for small co-axial helicopters [8]. Autonomous recharging capabilities are exhibited through iRobot's commercially available floor cleaning robot, "Roomba" which autonomously navigates to a charging dock [9]. A few other ground robots also have similar autonomous recharging capabilities, but a mainstream application for UAVs has still not been successfully deployed. Researchers at the Massachusetts Institute of Technology [5,6] and ETH Zurich [10] have been working towards persistence missions with autonomous recharging stations for UAVs. However, all these works use a contact-based charging station which requires the mechanical contact through electrodes for the connection and charging of a UAV. One negative side of this contact-based charging requires precise landing of the UAV on the charging station in order to ensure the charging contact which eventually increases the control complexity and cost. Also the mechanical design and implementation of the contact-based charging station increases the manufacturing cost and the design complexity [11].

Nowadays, wireless power transfer (WPT) is a famous technique being used in many low-power charging applications for smartphones and other electronic devices [12,13]. The strongly coupled magnetic resonant induction for WPT allows efficient and high power transmission to the distances up to 2 m [12]. Magnetic resonant induction-based WPT has little interference and disturbance with its environment, and its omni-directional characteristic motivated for the application to UAVs [13]. Also the concept of WPT has been used where UAVs power sensor networks wirelessly [14]. All these works present the successful application of WPT in various (yet, mainly low-power) applications. This success of WPT technology, mentioned in the above studies, motivates the present proposition of using relatively high-power WPT technology in enhancing the persistency of the UAVs for longer flight times. Integration of WPT in the UAVs is expected to provide the ability of automatic recharging and longer flight times without human intervention, which is the novelty of the proposed research.

Along with the progress in the WPT technology, the flight controller for a multicopter used for research purposes has been also developed with the ability to be controlled wirelessly from a ground station [1–3]. This flight controller development procedure often requires a great deal of time and cost, but the present study presents a low-cost and easily implementable solution which works for any commercially available multicopter, and allows for wireless communication between the multicopter and a PC-based ground station equipped with MATLAB software. This solution provides an interface with a VICON (infrared camera) motion capture system [4] for implementing different high-level control algorithms for autonomous navigation, path planning or formation flight.

The flight controller for multicopters takes care of attitude (inner-loop) and position (outer-loop) control. The inner-loop control part is usually implemented on the on-board processor of the multicopter, whereas the outer-loop part is on that of the ground station. Both inner-loop and outer-loop control parts are often developed by research groups for implementing their own control algorithms [3,15]. Developing the inner-loop control part for a multicopter, however, is a hard task, and it increases the computational cost and complexity especially when the inner-loop control design of the multicopter is not the research aim. As the research aim of the present study focuses on the outer-loop control of a multicopter, the proposed flight controller in this paper adopts a commercially available product (whose source code is open to public [16]) for the inner-loop part, and only its outer-loop part and the interface between the two parts are mainly focused on by the present study. In order to achieve the outer-loop control with the interface, a precise position-feedback mechanism is required for allowing a multicopter to perform even acrobatic moves such as multi-flips, as developed by D'Andrea et al. [3].

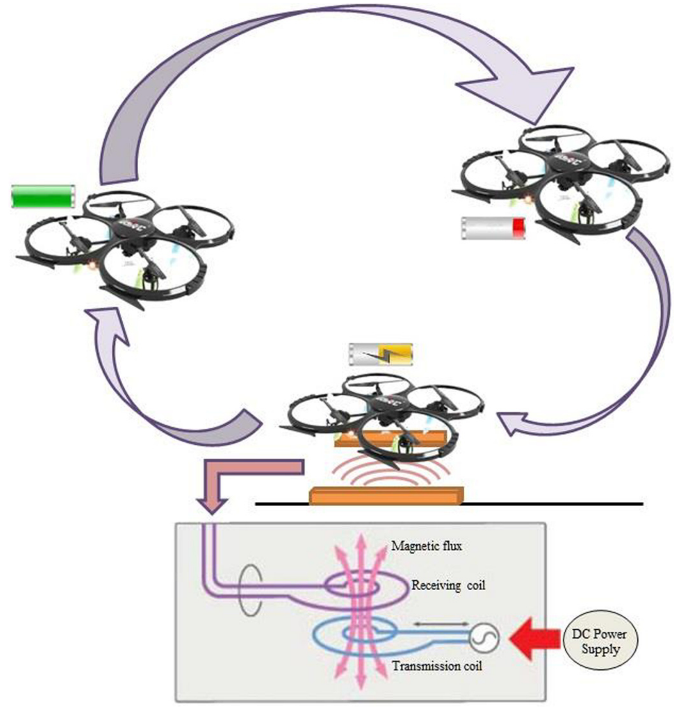

Fig. 1.2. Concept of the proposed solution.

The VICON motion capture system [4] is often used as a system for ground truth [3,15,17–23]. This motion tracking system is based on multiple cameras, with very high frame rates (from 120 to 1000 fps), capable of detecting even tiny movements of a multicopter. In a well-calibrated environment, it is indeed possible to perform the acrobatics viewed in [24]. The flight control electronics applied in the present research enables the intended precise outer-loop or position control and the interface using this VICON motion capture system.

In conclusion, this paper proposes a cheap solution for multicopters to prolong the flight time for persistent missions by using a wireless charging station allowing autonomous navigation and charging without any human intervention. For this purpose, a fully autonomous multicopter is first built using a new interface technique connecting a commercial on-board inner-loop controller and a ground station (PC) running Matlab software. Then by using the WPT technique, a landing station is built for the multicopter to charge the multicopter's battery wirelessly (without any constraints of wire connections). Also, automatic detection of the low charge on a multicopter will direct the multicopter to the charging station. In other words, a multicopter will be able to detect its low energy level during the mission and start landing onto the station for recharging. After the successful recharging, it will fly off from the station to resume the mission. Fig. 1.2 illustrates this concept, and Table 1 summarizes the contributions or new trials made in this paper.

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