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Development of micro-UAV with integrated motion planning for open-cut mining surveillance

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ABSTRACT

Small unmanned aerial vehicles called micro-UAVs are excellent examples of cyber-physical systems which interact with complex and dynamic environments. The success of this technology depends on smart avionics systems compensating for the physical limitations of small airframes, which have very limited on-board power. This paper presents development of micro-UAV for surveillance of open-cut mining sites that represent significant challenges due to difficult terrain and changing wind conditions. The real time aircraft control is integrated with motion planning based on Rapid-exploring Random Tree (RRT) methods which allow efficient handling of the wind factor. The main computational difficulty with RRT in real time motion planning is overcome by employing reduced forward model (RFM) of the aircraft. We also outline some strategies on integrating motion planning, control, and payload processors in reconfigurable hardware to optimise performance and power consumption. The micro-UAV development process is incremental and in large part based on simulations with hardware in the loop but gathering data from experimental flights is essential for accurate reduced forward models. We developed the avionics and experimental vehicle and used it in surveillance missions over mining sites to validate our approach.

1. Introduction

Micro Unmanned Aerial Vehicles (μUAVs) that can be defined as UAVs weighing less than 2 kg, have enormous potential in all kind of applications where a small, safe, easy to handle and cheap air vehicle can be used instead of a manned airplane.

The principle commercial application of μUAVs is short term placement of airborne sensors, e.g. camera or gas sensor, in inaccessible locations which are currently economically infeasible or too dangerous to monitor with other methods. Target missions are often dangerous or tiring for human pilots and include routine monitoring of mining operations, early information on natural disasters, remote sensing of inaccessible or dangerous terrain. An example might be updating sub-decimetre photogrammetric 3D models of mine pits at a weekly time scale to track high wall stability, production volumes and blasting efficiency. In these applications μUAV s are required to operate in complex and constrained airspace that is subject to physical obstructions and severe atmospheric boundary layer effects.

Micro UAVs require a complex compromise of safety, stability, power, endurance and effective payload. As aircraft become smaller, kinetic energy is lowered and agility increases but stability, endurance and payload experience severe constraints. These autonomous vehicles are excellent examples of cyber physical systems, which interact with complex environments and require sophisticated control strategies to overcome their physical limitations and achieve the mission goals. The design of these vehicles must also be innovative and quite often unorthodox since the limited power on-board limits both physical performance and computation capability.

Accurate airborne sensor placement and routine operation might be achieved by a number of approaches. Firstly, the physical and meteorological operating conditions of a given μUAV may be defined such that all operations will be within a wide margin of platform capability limits. This will severely limit platform operation to all but the most benign locations. A second approach relies on highly experienced pilots understanding near surface atmospheric conditions and making judgement calls regarding path planning during the flight. This approach cannot assess whether flight paths are optimal or even effective during the flight and relegates μUAV use to expensive, expert and professional applica-

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tions. A third, data intensive approach, combines accurate µUAV flight dynamics, detailed topography, surface obstacles and micro meteorological models to simulate flight paths allowing deterministic path planning. But, there is a low probability the µUAV will experience the modelled conditions during physical operation given airspace complexity.

This paper explores a fourth approach where flight path planning and µUAV flight performance are continuously updated online using 3/4D restricted airspace, hierarchical state control framework and integrated motion planning algorithms. This approach defines local reachability in current conditions and provides non-deterministic, revisable and near optimal solutions for achieving required platform and sensor states. Factors in this model include current and goal states, time/power cost, instantaneous meteorological conditions and flight dynamics.

There is a substantial body of research focused on aerial vehicle control and navigation systems capable of on-line path planning with model predictive control. Dubins curves, commonly used for model approximations [1] and trajectory primitives [2] do not take into account wind disturbance and asymmetries that may exist in the UAV's dynamics. Full state models such as implemented in JSBSim [4] are too expensive computationally for online operations.

Sampling based methods in output-space, such as Rapidly-exploring Random Trees (RRTs) introduced in [3], use a forward control object model to estimate the future states given a desired position input. In [14] the authors describe an RRT based planner with a full dynamic model of a blimp for trajectory generation in simulation. For real time control of micro-UAVs this approach fails since the sampling based process uses the model in a tight iteration loop and the model must be computationally very efficient.

Doshi et al. [5] introduced a Reduced-order Forward Model (RFM) that predicts the position of a UAV on a local time horizon, given a waypoint command and a local wind estimate. The method is especially useful for applications that require a computationally efficient and accurate prediction, taking into account detailed UAV dynamics. We apply this method in our motion planning platform.

Sophisticated control of micro-UAVs requires computing platforms capable of real time computations with complex algorithms. Power consumption of standard microprocessors is excessive for high speed computations and draws on the total energy which can be used to power the vehicle. Specialised processors or direct hardware implementation of algorithms can provide the required speed at lower power consumption. This is why there is strong research interest in specialized computing platforms for robotic and UAV control applications.

In [6] a hybrid architecture FPGA–DSP processor was proposed and tested in flight. The FPGA soft core NIOS processor with FIFO buffers was used for communication with the external DSP processor which undertook most of the computation although path planning was not implemented. In [7] the dedicated FPGA based motion planning processor was developed based on a probabilistic road map method. An interesting aspect of this work is capacity for the FPGA design to be reconfigured for collision detection.

An FPGA implementation of simulation based Nonlinear Model Predictive Control (MPC) is presented in [8]. The specially designed hardware core performs numerical integration and is interconnected with a soft core implemented on the same FPGA. The hardware core is implemented in Handel-C and computations are integer based. The design was tested on a Hardware-in the-Loop test-bed with XPC simulator but not in flight.

One of the latest reports [9] provides an in depth analysis of MPC based on FPGA. The system consists of a sparse structure exploiting an interior point quadratic program solver for model predictive control and for steady-state target calculation. The control algorithms targeted a large aircraft and as such are not directly applicable to micro-UAVs. The result is interesting, however, since it proves that even high complexity algorithms for sophisticated control can be implemented on mid-range FPGAs.

This paper provides an overview of a micro-UAV computational platform and its development process. The target application of our micro-UAV is surveillance of open-cut mining sites containing difficult terrain and wind conditions. This is why it is essential that the platform integrates aircraft control and motion planning in wind. We have chosen motion planning based on RRT since it is one of the most promising methods. We also have overcome the main computational difficulty with RRT in real time path planning by employing reduced forward aircraft model, which proved to be adequate for precision control. The development of our platform is incremental with FPGA hardware replacing parts of microcontroller based implementation previously tested in flight. All hardware modules are tested as hardware in the simulation loop before transferring to the flying platform.

In Section 2 we provide a simplified RRT method with RFM. Section 3 presents details of the development platform and applied methodology, while Section 4 presents experimental data. Section 5 summarizes the paper and outlines future work.

2. Online motion planning with RRT

RRT were first introduced in [4] to explore the possibility of applying the dynamics of a non-holonomic system directly to motion planning. In this approach, a tree is incrementally expanded towards randomly sampled points in the search space via forward simulation of a control input into the dynamic model of the system.

Small UAVs are primarily used to collect information related to on ground occurrences and as such are subject to factors such as model uncertainty and external disturbance (wind and gust). This requires online motion planning to address changes in the system. Using a high fidelity model to describe the dynamics of a system can be computationally infeasible, but a robust simplified model can be used while still obtaining satisfactory performance as shown in [15]. In order to increase computational efficiency in online motion planning on a small computing platform the use of a RFM is proposed in [5]. This model takes into account both the closed loop controller and steady wind disturbance. The model is a polynomial approximation with coefficients computed through extensive simulations of the UAV model. Given a set of initial con-

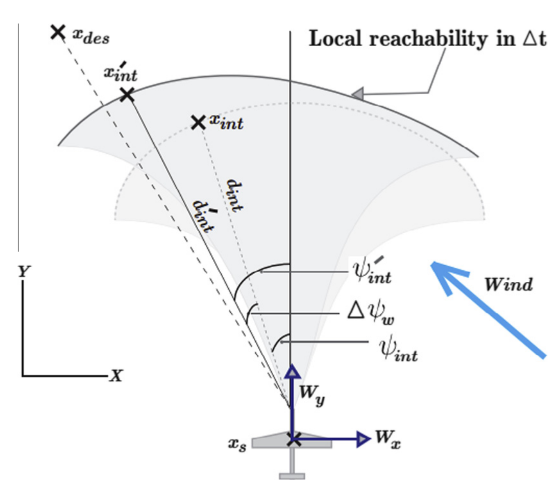

Fig. 1. RRT with RFM to predict UAV position.