HYBRID CONTROL OF AN AUTONOMOUS HELICOPTER

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Abstract. This paper proposes a hierarchical hybrid architecture of a reactive system that governs the operation of a helicopter based UAV. The mission of the helicopter is to search for, investigate and locate objects in an unknown environment. To perform visual navigation, the helicopter is equipped with a Flight Vehicle Management System(FVMS) and a vision system that scans the ground for objects and landmarks. Hybrid system combines continuous dynamics with discrete automata, and therefore provides a congenial framework to integrate planning, vision and control. Computer Aided Design tools for real-time embedded systems enhance the conception and verification of the FVMS.

Key Words. Hybrid system, Flight mode management, Unmanned aerial vehicle

1. Introduction

For vision based navigation tasks, such as inspection of power lines, terrain surveying, and investigation of hazardous waste sites, an Unmanned Aerial Vehicle (UAV) requires high manœuvrability and the ability to perceive and perform reasoning about the environment.

Helicopter(Prouty, 1995; McCormick, 1995) offer the significant advantage over traditional air vehicles, in that they provide extended manœuvrability, such as vertical climb, hovering, longitudinal and lateral flight, hovering turns and bank turns. These manœuvres constitute a repertoire of basic flight modes which are combined to execute more complex navigation behaviors such as localization and inspection of ground objects.

Depending on the context of operation, the FVMS activates different flight mode controllers that emphasize on certain performance aspects, such as safety of operation, tracking accuracy, execution of aggressive manœuvre, disturbance rejection and robustness in regard to unmodeled dynamics. (Shim *et al.*, 1998) employ three different control methodologies μ-synthesis, genetic-fuzzy systems and feedback linearization in order to provide a wide range of controllers designed for various operating conditions.

This paper deploys the architecture of a Flight Vehicle Management System(FVMS) that integrates planning and control. The FVMS was first proposed for smart aircrafts in future Air Traffic Management Systems(ATMS)(Sastry *et al.*, 1995) for decentralized air traffic control. The FVMS is responsible for resolving conflicts among air vehicles, planning of the flight path, generating a proper sequence of flight modes, calculating a feasible trajectory and regulating the helicopter along the nominal trajectory.

The vision system captures objects in the environment that provide guidance to the helicopter. The vision system permanently scans the ground and notifies the FVMS about the location of objects and landmarks detected. Vision plays an essential role whenever the helicopter is required to navigate based on local perceptions, such as investigating objects of interest.

The hierarchical control scheme enables the interaction of continuous dynamics with discrete events. Reasoning and decision mak-

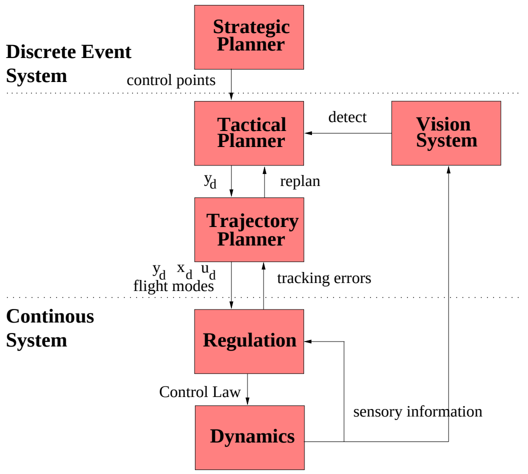

Fig. 1. Proposed Architecture for a helicopter based UAV

ing about the helicopter operation require a discrete representation, while the underlying dynamics of the helicopter and lower level controllers are described by differential equations and continuous control laws. Since flight control systems have comparable functional and hierarchical complexity, systematic design tools are necessary in order to verify that the control schemes meet the performance specifications.

2. System Architecture

The system consists of three parts: the FVMS which is responsible for planning and controlling the operation of the helicopter, the vision system for detection and investigation of objects and the helicopter platform.

2.1. *Flight Vehicle Management System*

The FVMS has a hierarchical architecture as shown in Figure 1 which consists of four layers, the strategic, tactical, and trajectory planners, and the regulation layer.

2.1.1. *Strategic Planner.* The Strategic planner resides on top of the FVMS and is concerned with the planning and execution of the central helicopter mission. The strategic planner commands the tactical planner to execute a sequence of proper behaviors which enable the helicopter to accomplish the overall mission. It designs a coarse, self-optimal trajectory which is stored in form of a sequence way-points. The strategic layer communicates with other FVMS in order to coordinate missions that require the cooperation of multiple helicopters.

2.1.2. *Tactical Planner.* The tactical planner is responsible for the coordination and execution of behaviors, such as landing, searching an area, approaching a way-point, collision avoidance or inspection of objects on the ground. The tactical planner is able to overrule the behavior proposed by the strategic planner, in case of safety critical situations such as collision avoidance, failure of sensors or strong wind gusts. The tactical planner returns to the original behavior as soon as the conflict among the prioritized safety manœuvre and the accomplishment of the mission is resolved.

In addition, the tactical planner refines the strategic plan by interpolating the way-points with a smooth output trajectory. The tactical planner uses a kinematic model of the helicopter for all trajectory calculations. The output trajectories of the kinematic model are then passed to the trajectory planner as desired output profiles.

2.1.3. *Trajectory Planner.* The trajectory planner decomposes the behavior commanded by the tactical planner into a sequence of primitive manœuvres, such as forward-, sideward-flight, hovering, vertical climb and turns. In addition, it computes a feasible nominal input trajectory for the continuous regulation layer. The trajectory planner has to guarantee a safe, smooth transition among flight modes, controlled dynamic variables and nominal input trajectories. These issues constitute the hybrid control problem that we address in more detail in section 3.

The trajectory planner uses a detailed dynamic model of the helicopter, sensory input, and the output trajectory, to design a full state and nominal input trajectory for the helicopter, and the sequence of *flight modes* necessary to execute the dynamic plan. These flight modes represent different modes of operation of the helicopter and they correspond to controlling different variables in the helicopter dynamics. The resulting trajectory, denoted y_d, x_d, and u_d in Figure 1, is given

Fig. 2. The free-body diagram of a helicopter in flight

are the main rotor collective pitch, tail rotor collective pitch, longitudinal cyclic pitch and lateral cyclic pitch, respectively.

The state equation consists of the translational and rotational kinematic and dynamic equations:

$$\begin{bmatrix} \dot{P} \\ \dot{V} \\ \dot{R} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} V \\ \frac{1}{m} R f^b + b_I g \\ R\hat{\omega} \\ \mathcal{I}^{-1}(\tau^b - \omega^b \times \mathcal{I}\omega^b) \end{bmatrix} \tag{1}$$

where $b_I = [0\ 0\ 1]^T$ and g is the gravitational constant. As shown in Figure 2, f^b and τ^b are the resultant force and torque acting on the body, respectively. Both force and torque are functions of the controls, u. For details, please refer to (Lee *et al.*, August 1993).

3. Hybrid Control Formulation

This section describes the hybrid control problem of integrating the continuous control laws and system dynamics with the discrete planning and decision making. In case of the helicopter, the hybrid system design has to consider multiple, sometimes conflicting objectives such as safety, efficiency, accuracy and reliability of operation. The synthesis of the hybrid controller is facilitated by the fact that these objectives have a hierarchical priority. Therefore, the system only pays attention to a low priority objective such as speed of manœuver execution in case the more important requirements such as stability are met. The issue of systematic verification of the performance specifications in hybrid control systems is beyond the scope of this paper.

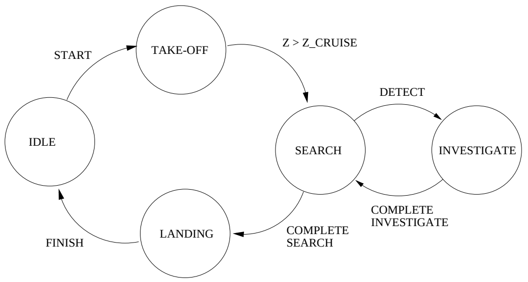

Fig. 3. State diagram of automaton in the tactical planner.

We refer the interested reader to (Lygeros *et al.*, 1995).

Every layer of the FVMS is concerned with a different type of discrete events and transitions. The tactical planner selects the dominant behavior according to the plan that constitutes the mission. However, it is able to overrule the proposed behavior proposed in case of external events such as the detection of an object or an obstacle. The trajectory planner introduces switching between different manœuvres depending on the commanded behavior and the context of operation. The regulation layer reacts to these flight mode transitions by activating a proper flight mode controller.

3.1. *Tactical Planner*

The tactical planner refines the strategic plan by interpolating the control points with a smooth output trajectory. The tactical planner uses a kinematic model of the helicopter for all trajectory calculation. As shown in (Koo and Sastry, 1998), the helicopter model is approximately input-output linearizable under some mild assumptions, with position and heading as outputs. One useful consequent of linearization is that the linearized system is decoupled. Therefore, we could obtain an abstraction of the system as four decoupled second order linear systems with inputs being the corresponding accelerations.

The tactical planner employs an automaton for the representation of the behavior of the physical system by discrete states. Figure 3 depicts the automaton for the search and investigate mission. A simulated helicopter trajectory including object detection and investigation is shown in Figure 4. The flight path is constituted by a sequence of vertical climb/descent, hovering, turns and forward manœuvres. In the beginning the helicopter switches from the initial idle state to the take-off state as soon as the FVMS receives the external start signal. When the helicopter reaches the commanded altitude Z_{CRUISE}, the automaton makes a transition to search state. In the search state the helicopter tracks a sequence of way-points connected by straight line segments. The trajectory planner subdivides these segments into a turn to align the helicopter heading with the direction to the next way-point, a forward flight to approach the way-point at a nominal cruise velocity and hovering once the way-point is reached. While in the search state, the vision system scans the ground for objects within the visible area, which depends on the camera viewing angle and the altitude. In the depicted scenario, when the vision system detects an object of interest, it triggers a detect event which is passed together with the object location to the tactical planner. As a result, the automaton state switches from search to investigate. The planner inserts the object location as a new way point into the flight plan. In addition, it stores the current position so that the helicopter can later regress to the original trajectory. The investigation behavior is composed of a turn, forward flight, hover and a vertical descent to enable a closer inspection and classification of the object. Afterwards, the helicopter climbs back to its cruising altitude and returns to the stored position. The planner switches back to search state and resumes its original trajectory. When the helicopter arrives at the final way-point of the flight plan, the automa-

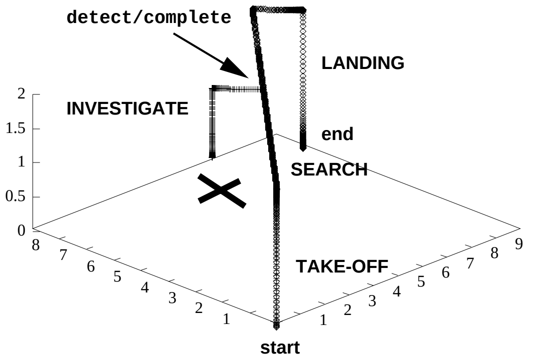

Fig. 4. Simulated helicopter trajectory, ground object is marked by ×.

ton switches to the landing state, which corresponds to a vertical descent. After the completion of the landing manœuvre the automaton returns to the idle state and shuts down the engine.

3.2. *Trajectory Planner*

The trajectory planner deploys a detailed dynamic model of the helicopter, sensory input and the output trajectory to generate a full state and nominal input trajectory and the sequence of flight modes necessary for executing the dynamic plan. The flight modes represent different modes of flight operation of the helicopter and correspond to controlling different variables in the dynamics.

Since the system is approximately input-output linearizable, the system can be shown(Koo and Sastry, 1998) to be differentially flat, *i.e.*all states and inputs can be expressed in terms of the (flat) outputs and their derivatives. Thus, the full state and nominal input trajectory can be generated by using the output trajectory given by the tactical planner.

Given an output trajectory, the trajectory planner assign an appropriate sequence of flight modes appended to the state-input trajectory for the regulation layer to execute. The transition among flight modes is restricted in sequence as shown in Figure 5.

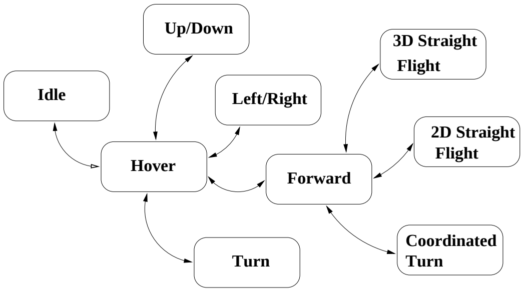

Fig. 5. Transition of flight modes

3.3. *Regulation*

For the controller in the regulation layer, we employed three different control methodologies to design controllers responsible for different types of flight modes and operating conditions. For the details of each design on the helicopter dynamical model, please refer to (Shim *et al.*, 1998).

For set-point regulation and mild trajectory tracking, we apply robust control using $\mu-$synthesis(Packard and Doyle, 1993). The control design emphasizes on a robust performance in regard to model uncertainties, sensor noise, parameter changes and external disturbances.

The genetic-fuzzy system approach allows the designer to specify his performance goals directly by means of a scalar objective function and releases him from a tedious manual tuning and optimization procedure (Hoffmann *et al.*, 1998). The method can be used to generate specific controllers that emphasize on different performance aspects such as robustness, accuracy and speed of execution.

Feedback linearization(Isidori, 1995) deploys a nonlinear dynamic model of the helicopter for the control design. The nonlinear controller is capable of tracking aggressive flight trajectories, since the design is applicable over the full operational flight envelope.

The performance of individual controller is relatively easy to be justified by applying nonlinear control theory. However, the analysis of the overall switched system is not straight forward. The problem becomes even more complicated when the interaction with external events that emerge at the tactical layer is taken into consideration.

4. System Design and Simulation

Various simulation software have been proposed for simulating hybrid system, which involves the interaction of continuous dynamics and discrete events. The POLIS(Balarin *et al.*, 1997) co-design environment developed by CAD group at Berkeley is targeted towards reactive, real-time control systems.The target domain of real-time control systems, the formal basis of Finite State Machine(FSM), and the interface to the verification tools make POLIS a useful tool for hybrid system design. POLIS is chosen as a design tool for FVMS on helicopter based UAV. The simulation is performed on Ptolemy(Buck *et al.*, 1994) developed by the DSP group at Berkeley with the modules developed from POLIS. Due to the flexibility on redesign of FSM on POLIS, system performance can be optimized based on simulation result.

Using POLIS and Ptolemy as design and simulation tools, a simulator will be developed for the flight mode management systems of multiple helicopters.

5. Conclusions and Future works

This paper presents the construction of a hierarchical hybrid architecture of a reactive system for a helicopter based UAV. The system is capable of vision based navigation. The paper formulates the problem of integrating planning, vision and control in the context of hybrid system theory. In the future, multi-objective hybrid controller design techniques will be developed for systematically synthesizing a hybrid controller to satisfy multiple requirements such as safety, saturation of states and fuel efficiency. Moreover, the FVMS will be extended to cope with the scenario of coordinating multiple helicopters acting as a group of intelligent agents(Tomlin *et al.*, August 1997). The implementation on an embedded system using POLIS will also be investigated.

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6. REFERENCES

Balarin, F., P. Giusto, A. Jurecska, C. Passerone, E. Sentovich, B. Tabbara, M. Chiodo, H. Hsieh, L. Lavagno, A. Sangiovanni-Vincentelli and K. Suzuki (1997). *Hardware-Software Co-Design of Embedded Systems: The POLIS Approach.* Kluwer Academic Publishers.

Buck, J. T., S. Ha, E. A. Lee and D. G. Messerschmitt (1994). Ptolemy: A framework for simulating and prototyping heterogeneous systems. *Int. Journal of Computer Simulation, special issue on Simulation Software Development* 4, 155–182.

Hoffmann, F., T. J. Koo and O. Shakernia (1998). Evolutionary design of a helicopter autopilot. In: *The 3rd On-line World Conference on Soft Computing (WSC3).*

Isidori, A. (1995). *Nonlinear Control Systems.* Springer-Verlag.

Koo, T. J. and S. Sastry (1998). Output tracking control design of a helicopter model based on approximate linearization. Submitted to the 37th IEEE Conference on Decision and Control.

Lee, E. H., H. Shim, H. Park and K. I. Lee (August 1993). Design of hovering attitude controller for a model helicopter. In: *IEEE Int. Soc. Instrument and Control Engineers.*

Lygeros, John, Datta Godbole and Shankar Sastry (1995). A game theoretic approach to hybrid system design. Technical Report UCB/ERL M95/77. University of California, Berkeley.

McCormick, Barnes W. (1995). *Aerodynamics Aeronautics and Flight Mechanics.* John Wiley and Sins, Inc.

Packard, A. and J. Doyle (1993). The complex structured singular value. *Automatica* **29**(1), 71–109.

Prouty, Raymond W. (1995). *Helicopter Performance, Stability, and Control.* Krieger Publishing Co., Inc.

Sastry, S., G. Meyer, C. Tomlin, J. Lygeros, D. Godbole and G. Pappas (1995). Hybrid control in air traffic management systems. In: *Proceedings of the 1995 IEEE Conference in Decision and Control.* New Orleans, LA. pp. 1478–1483.

Shim, D. H., T. J. Koo, F. Hoffmann and S. Sastry (1998). A comprehensive study on control design of autonomous helicopter. Submitted to the 37th IEEE Conference on Decision and Control.

Tomlin, Claire, George J. Pappas and Shankar Sastry (August 1997). Conflict resolution for air traffic management: a study in multi-agent hybrid systems. *Accepted as a regular paper in the IEEE Transactions on Automatic Control.*