

## AUTONOMOUS FLYING VEHICLE RESEARCH AT THE UNIVERSITY OF SOUTHERN CALIFORNIA

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**Abstract** This paper outlines research on Autonomous Flying Vehicles at the University of Southern California(USC). We are particularly interested in control strategies for autonomous vehicles to perform difficult tasks such as autonomous landing and trajectory following. In addition we are starting research on cooperative algorithms for formation flight with a group of autonomous flying robots. In particular, we present the design and behavior-based control architecture for an autonomous flying vehicle (AFV), for vision-based landing. We use vision for precise target detection and recognition as well as combination of vision and GPS for navigation. An outline of the reference design of an autonomous helicopter for research in formation flying is also presented. A discussion of exemplar algorithms used for controlling multiple robots in formation is presented.

**Keywords:** Autonomous Flying Vehicle, Formations, Vision-based landing, Multiple Robot Coordination

### 1. Introduction

A basic requirement for autonomous flying vehicles(AFVs) is robust autonomous flight, for which *autonomous landing* is a crucial capability. The problem of autonomous landing is particularly difficult because the inherent instability of the helicopter near the ground [Shakernia et al., 1999]. Also since the dynamics of a helicopter are non-linear only an approximate model of the helicopter can be constructed [Conway, 1995]. [Garcia-Pardo et al., 2000] discusses a vision-based solution to safe landing in unstructured terrain where the key problem is for the onboard vision system to detect a suitable place to land, without the aid of a structured landmark such as a helipad. [Sinopoli et al., 2001] have demon-

strated tracking of a landing pad based on vision but have not shown landing as such.

At the same time very little research has been performed in the area of coordination of multiple AFVs. AFV systems tend to be expensive and complex and therefore just having one system is considered a major accomplishment. Why fly in formations? Beside the challenge of accurately controlling multiple robots, there is the added benefit of having the coordination of multiple sets of sensors. Nature favors animals that have the ability to form formations such as flocks of birds or schools of fish. Animals that can combine their sensing abilities have shown to better avoid predators and efficiently forage for food [Balch and Arkin, 1998]. Both the Air Force and NASA have identified autonomous formation of spacecraft as key technological milestones for the 21st century [Beard et al., 2000]. Applications of spaced based autonomous vehicles range from ground surveillance to interferometry experiments.

Our research spans from developing better sensing capabilities to algorithms for multi-robot formations. The AVATAR(Autonomous Vehicle Aerial Tracking And Reconnaissance) project has been an ongoing research project at USC for the past ten years. The primary focus of the AVATAR project has been developing greater sensing and control capabilities for a single UAV, while at the same time cooperation and coordination with ground based robots. For a description of the research regarding multi-robot coordination between aerial and ground vehicles the reader is referred to [Sukhatme et al., 2001]. The project has recently reached a major milestone; it is the first UAV that has landed autonomously under vision-based control. The RAPTOR(Research on Aerially Precise Teams of Robots) project at USC has begun investigating multi-robot formation control. In particular we plan on utilizing small electric-powered radio-controlled (R/C) model helicopters as a mechanical chassis for our design. Relative localization of each robot will be accomplished using only local sensing (CMOS camera). In contrast to global localization techniques (GPS), each robot will only have knowledge of its relative location with respects to one or more of its neighbors. This will be beneficial in environments where GPS is not available (i.e. indoors or between skyscrapers).

In this paper we present two different facets of our research. The first part of the paper describes the use of vision coupled with Inertial Navigational System to perform autonomous landing. The second part of the paper describes our ongoing research in the field of formation flying using AFVs.

## **2. The AVATAR Testbed**

Our experimental testbed AVATAR (Autonomous Vehicle Aerial Tracking And Reconnaissance) [Montgomery, 1999] is a gas-powered radio-controlled model helicopter fitted with a PC-104 stack augmented with several sensors

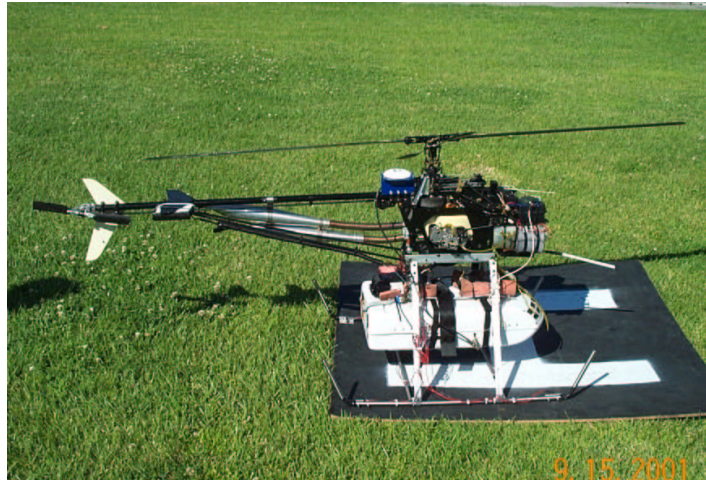


Figure 1. AVATAR (Autonomous Vehicle Aerial Tracking And Reconnaissance)

(Figure 1). A Novatel RT-20 DGPS system provides positional accuracy of 20cm CEP(Circular Error Probable, i.e. the radius of a circle, centered at the true location of a receiver antenna, that contains 50% of the individual position measurements made using a particular navigational system). A Boeing CMIGTS-II INS unit with three axis accelerometers and three-axis gyroscopes provides the state information to the on-board computer. The helicopter is equipped with a color CCD camera and an ultrasonic sonar. The ground station is a laptop that is used to send high-level control commands and differential GPS corrections to the helicopter. Communication with the ground station is carried via 2.4 Ghz wireless Ethernet and 1.8Ghz wireless video.

### 3. Control Architecture

The AVATAR is controlled using a hierarchical behavior-based control architecture. Briefly, a behavior-based controller [Mataric, 1997] partitions the control problem into a set of loosely coupled behaviors. Each behavior is responsible for a particular task. The behaviors act in parallel to achieve the overall goal. Low-level behaviors are responsible for robot functions requiring quick response while higher-level behaviors meet less time critical needs. The behavior-based control architecture used for the AVATAR is shown in Figure 2.

At the lowest level the robot has a set of reflex behaviors that maintain stability by holding the craft in a hover condition. A detailed description of the architecture can be found in [Montgomery, 1999]. A key advantage of such a

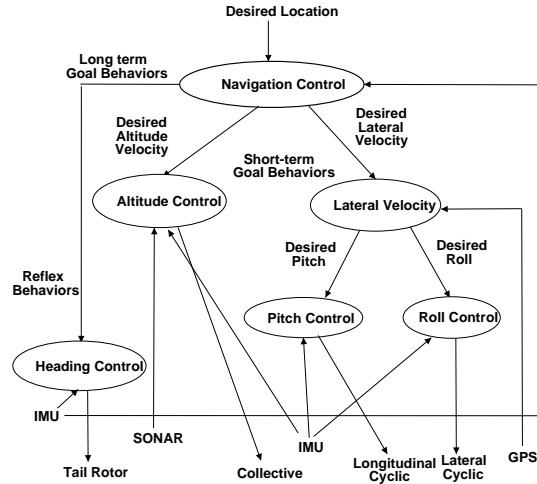


Figure 2. Behavior Based Controller

control algorithm is to build complex behaviors on top of the existing low level behaviors.

The low-level and short-term goal behaviors *roll*, *pitch*, *heading*, *altitude* and *lateral control* behaviors are implemented with proportional controllers. The long-term goal behavior *navigation control* is responsible for overall task planning and implementation. If the heading error is small, the *navigation control* behavior gives desired lateral velocities to the *lateral velocity* behavior. If the heading error is large, the *heading control* behavior is commanded to align the helicopter with the goal while maintaining zero lateral velocity.

#### 4. Vision-based State Estimation

This section deals with the vision algorithms implemented for autonomous detection, tracking of a helipad and landing on it. The images obtained from the camera are noisy and the frame grabber is of low quality, hence we work with binary images to reduce the computational cost and increase the effectiveness of the algorithm. This is done by thresholding and filtering the image. The image obtained after thresholding and filtering may consist of objects other than the helipad. In the next step the various regions of interest are identified and labelled. The next stage involves the detection of the landing pad (in our case a Helipad) using geometric invariants. Geometric shapes possess features such as *perimeter*, *area*, *moments* that often carry sufficient information for the task of object recognition. Based on the geometric features of an object one can calculate a set of descriptors which are invariant to rotation, translation and scaling.

One such class of descriptors [Hu, 1962] is based on the moments of inertia of an object. These descriptors are used for locating the helipad. For a detailed description of the algorithm the readers are referred to [Saripalli et al., 2002]. After the helipad is located, the state estimation algorithm calculates the coordinates and orientation of the landing target relative to the helicopter. These state estimates are sent to the helicopter controller.

#### 4.1 Controller for Autonomous Landing

The controller described in Section 3 is modified as below to perform vision-based landing. The *altitude control* behavior was split into three sub-behaviors, *hover-control*, *velocity-control* and *sonar-control*. The *hover-control* sub-behavior is activated when the helicopter is either flying to a goal or is hovering over a particular target. This sub-behavior is used during the object recognition and object tracking state when the helicopter should move laterally at a constant altitude. The hover controller is implemented as a proportional controller. It reads the desired GPS location and the current location and calculates the collective command to the helicopter.

Once the helipad has been located and the helicopter is aligned to the object the *velocity control* sub-behavior takes over from the *hover-control* sub-behavior. It is implemented as a PI controller. An integral term is added to reduce the steady state error. The helicopter starts to descend till reliable values are obtained from the sonar. The *sonar-control* sub-behavior takes over at this point until touchdown. This is also implemented as a PI controller. Results based on flight data from field tests show that our method is able to land the helicopter on the helipad repeatably and accurately. On an average the helicopter landed to within 31 cm position accuracy and to within  $6^\circ$  in orientation as measured from the center of helipad and its principal axis respectively. Results also show the robustness of the algorithm, which allows the helicopter to find the helipad after losing it momentarily. They show that the algorithm is capable of tracking a moving landing target and land on it, once it has stopped. In these experiments the helipad was moved a significant distance (7 m on an average). For a detailed discussion on the results and the accuracy of the controller, refer to [Saripalli et al., 2002]. In the next section we describe our ongoing research on the use of autonomous flying vehicles for formation flying.

### 5. RAPTOR

Research on Aerially Precise Teams of Robots (RAPTOR) has developed a reference platform for research of multiple robot formations. Instead of building several large scale models such as the platform used by the AVATAR project, we have opted for a new platform based on a small electric model helicopter. The next two sections outline the design decisions that were made.

## 5.1 RAPTOR Mechanics and Avionics

After surveying many different R/C model helicopters, we decided on the Lite Machine's LMH-110 as our mechanical chassis. This small model helicopter is only 67 cm long. It has a 60 cm main rotor blade diameter and weights approximately 800 grams without batteries or any additional avionics. Early tests demonstrated its ability to lift more than half kilogram of payload. It is inexpensive, reliable and replacement parts are readily available from many mail order retailers and hobby shops. The platform avionics consist of several modules interconnected via a high-speed serial bus. The Inter-IC (I2C) Bus was selected as the mechanism by which each module would communicate to one another. Each module will have a dedicated micro-controller that provides the interface to the I2C bus. This will allow us to design, construct and test each module independently.

When selecting electronic components for these modules, there are three constraints that need to be taken into account. First, the overall size of the components must be kept as small as possible. Since we planned on using standard printed circuit boards that can be purchased at any Radio Shack store, we needed to "budget" the size of individual components to just those that would fit on these boards. Second, the components should be as light as possible. Third, each component should consume as little power as possible. High power consumption equates to more battery weight.

The choice of micro-controllers was a key early decision in our design phase. Ideally we wanted to use a single controller for all modules. Unfortunately, no single choice was perfect for all cases. However, we were able to limit ourselves to two choices; Atmel's Mega163 AVR controller and Scenix's SX28 processor. The Atmel Mega163 is one of the latest of highly integrated controllers from Atmel's Advanced RISC (AVR) line of micro-controllers. The Scenix SX28 is the fastest 8-bit micro-controller currently on the market. It can be clocked from four to 100 Mhz. Both controllers are programmable using standard "C" and development tools are freely available. Our current list of modules includes communications, actuator interface, inertial sensors, camera-laser-sonar interface, and a master controller.

## 5.2 Relative Localization

In order to maintain formation, each vehicle must know its position relative to some key location within the formation (often the location of the leader craft). While GPS receivers and global communications are one solution to this problem, there are limitations to GPS. GPS requires a direct line of sight between the receiver and at least four NAVSTAR satellites. This precludes its use indoor as well as between tall buildings. GPS receivers require as much as ten watts of power and require an antenna that is considerably bulky for small vehicles. In

contrast, CMOS cameras are extremely small, light weight, and require only an illuminated area. However, a single camera is rarely able to ascertain absolute global positions. Fortunately for us, we need only relative positions to maintain a formation. Our approach to vehicle localization within a formation is vision-based. Each vehicle is equipped with a downward pointing camera with a large field of view (FOV) lens. In addition, each vehicle is also equipped with an inexpensive laser pointer. Each laser pointer is attached to the vehicle in a manner such that it projects a signature (image) onto the surface below. The signature projected will be a plus (+) so that it can easily be distinguished from other features on the ground. Each laser pointer can be modulated to distinguish one vehicle's projection from another. This approach has several important merits. First, the 3D sensing problem has been effectively reduced to a 2D problem. This greatly reduces the required computation required for the vision detection system. Second, the number of sensors has been reduced to a single downward pointing camera.

### 5.3 Formation Control

Our research in control of formations of aerial robots, will concentrate on developing robust and scalable solutions. Initially we will concentrate on maintaining simple planar geometric shaped formations such as wedges and diamonds. These formations have long been used as benchmarks for formation studies in ground based formations [Balch and Arkin, 1998], [Fredslund and Mataric, 2001]. However, unlike traditional control strategies that utilize direct sensing or global positioning, our techniques will only rely on local sensing. Later, we will investigate techniques for dynamical changing of formations and maintain formations in the presents of obstacles We plan on validating our ideas both in simulation with tens of robots as well as with a few physical robots.

For any given formation, there are two types of participants: leaders and followers. The leaders of a formation occupy the control points of the formation. The overall direction of motion and orientation of a formation is defined by the formation's leaders. The followers create line segments at specified angle with respect to the leader. A formation can be defined as one or more sets of leader/followers.

With only local sensing of projected signatures on the ground, any given robot will only "see" a small set of its neighbors. Therefore any given follower robot may not be able to see a leader and will need to maintain a heading and distance from one of the robots it can sense. Although there will be global communication between members of the formations, the bandwidth is very limited and therefore broadcast messages will be kept to a minimal.

## 6. Conclusions

This paper describes ongoing research on autonomous flying vehicles at the University of Southern California. We have successfully demonstrated landing in unstructured terrain based on vision and GPS. In the future we plan to focus our attention on the problem of safe and precise landing of the helicopter in unstructured harsh 3D environments. The applications of such a system are enormous; from space exploration to target tracking and acquisition. We are starting research in multi-robot aerial vehicle formation flying. The research platform for such experiments has been presented and some initial ideas for formation flying have been proposed.

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