Autonomous Cargo Transport System for an Unmanned Aerial Vehicle, using Visual Servoing

Noah KUNTZ
Electrical and Computer Engineering, Drexel University
Philadelphia, PA 19104, USA

Paul OH
Mechanical Engineering, Drexel University
Philadelphia, PA 19104, USA

ABSTRACT

This paper presents the design and testing of a system for autonomous tracking, pickup, and delivery of cargo via an unmanned helicopter. The tracking system uses a visual servoing algorithm and is tested using open loop velocity control of a six degree of freedom gantry system with a camera mounted via a pan-tilt unit on the end effecter. The pickup system uses vision to direct the camera pan tilt unit to track the target, and uses a hook attached to a second pan tilt unit to pick up the cargo. The ability of the pickup system to hook a target is tested by mounting it on the Systems Integrated Sensor Test Rig gantry system while recorded helicopter velocities are played back by the test rig. [1]

INTRODUCTION

Autonomous unmanned helicopters are a valuable robotic platform owing to their flexibility when maneuvering in restricted environments. An unmanned helicopter would be ideally suited as a delivery vehicle for payloads needed in combat and civilian missions. Manned helicopters are frequently used for rapid transport of cargo that is oversize, overweight, or which is needed very quickly in the field. However cargo transport by a manned helicopter is a dangerous task that requires a great deal of training and entails risk to both the pilot and ground crews [1]. Issues include stabilization of the cargo while in flight, dangerous attachment and detachment procedures, and often flight through dangerous areas.

The autonomous system can pick up and deploy the cargo without the risk to ground crews, and no flight crew is put at risk if the cargo must be delivered to a dangerous area. An autonomous cargo transport system based on an unmanned helicopter would also allow very targeted delivery of key supplies. Unmanned helicopters with significant autonomous capabilities already exist (fig 1), so the cargo pickup mechanism itself would be the main design challenge. The cargo pickup mechanism is being developed and tested using a 6 Degree of Freedom (6DOF) gantry system. This paper will extend upon this work previously discussed by the authors in [2] and [3].

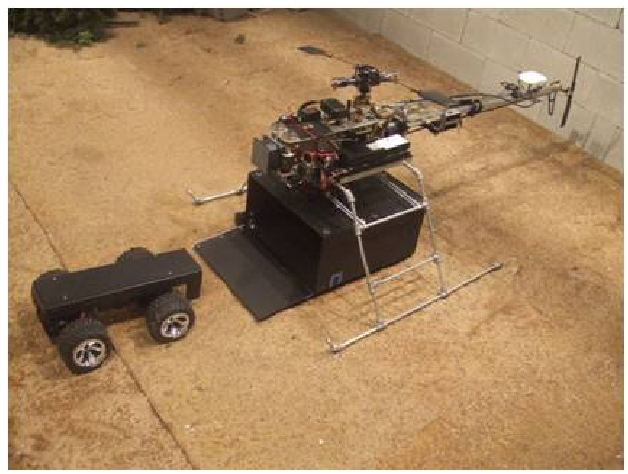

Figure 1. A belly-mounted docking station permits the robotic helicopter to aerially transport an unmanned ground vehicle

RELATED WORK

The combination of unmanned aircraft with computer vision systems has been frequently studied. The control of

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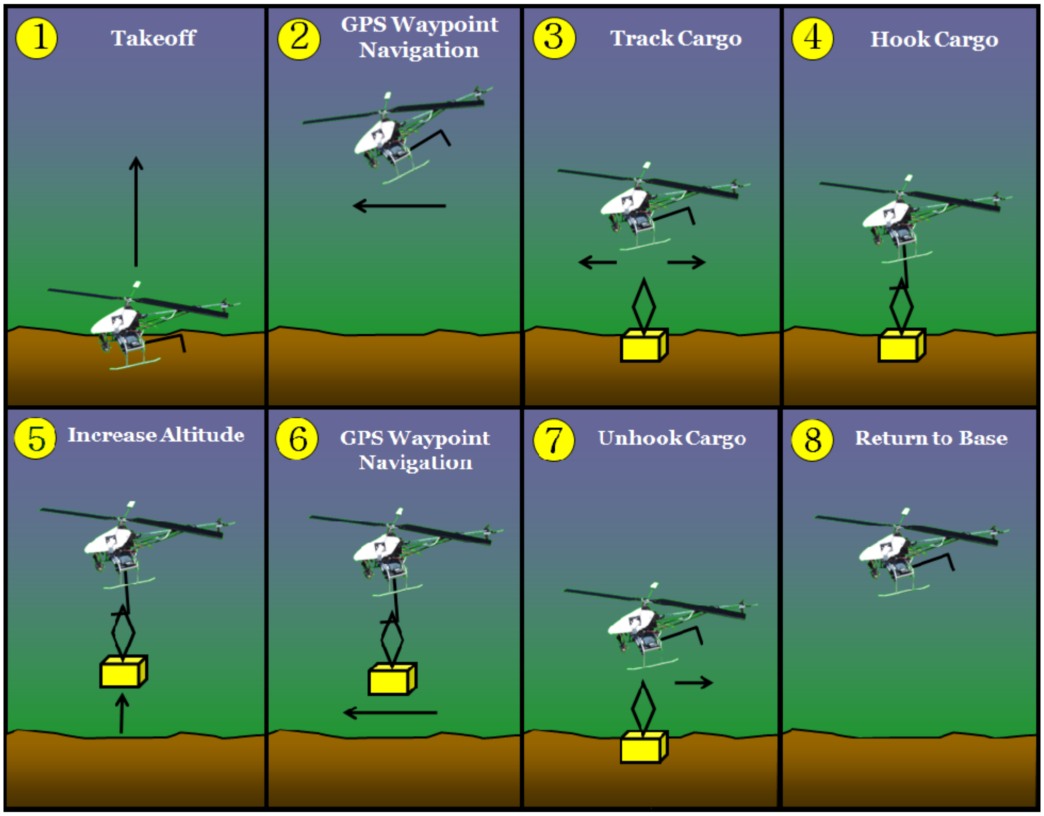

Figure 2. Eight phases for the notional concept of operations (CONOPS) of autonomous air cargo transport

pan tilt cameras mounted on helicopters has been examined, including the use of biomimetic control systems [4]. Such systems use gyros to detect sudden accelerations and react by moving the pan tilt unit in much the same way that the brain moves the eyes in response to forces experienced by the inner ear. This is similar to tracking the target while the helicopter is wandering during hover. General visual feature tracking by an unmanned helicopter has been developed and tested successfully [5]. There have also been some efforts to develop other autonomous cargo transport systems for example a plane/helicopter "tail-sitter" [6]. The focus of that work was on the aerial platform while the focus of the authors is the mechanism for picking up the cargo. Vision based landing of an unmanned helicopter has also been the topic of several papers. The primary focus of the authors is the tracking portion of the mission and the carrying of the cargo, without actually landing. Nevertheless some of the work regarding vision based landing is related in that it utilizes tracking of a ground based object by an unmanned helicopter. Visual tracking and landing on a moving target has been accomplished [7].

CONCEPT OF OPERATIONS

The goal of the author's research is a system capable of performing a complete autonomous cargo transport operation. The concept of operations for this system is presented in figure 2. The first stage of the mission is autonomous takeoff. Stage two is GPS waypoint navigation to the location of the cargo to be picked up. Collision avoidance would be used in ideal circumstances but that is beyond the scope of this research. In stage three the helicopter tracks the cargo while hovering over it, to correctly align the hook mechanism. Computer vision is used for the tracking operation. Stage four is the servoing of the hook mechanism to pick up the cargo. In stage five the helicopter lifts the cargo clear of the ground. In stage six the helicopter again uses GSP waypoint navigation, this time to navigate to the destination of the cargo. Stage seven is the drop off of the cargo, the helicopter descends until the cargo touches the ground and the load is off the hook, then pulls back the hook. Lastly, in stage 8 the helicopter returns to its base or conducts another mission. This is the procedure the authors are attempting to carry out autonomously.

CARGO PICKUP MECHANISM AND CONTROLLER

A prototype of the cargo pickup mechanism was constructed. This does not include the helicopter itself, just the camera and hook mechanisms and the control electronics. The mechanism is shown in figure 4. It consists of a camera mounted on a pan tilt unit (PTU), a hook mounted on a

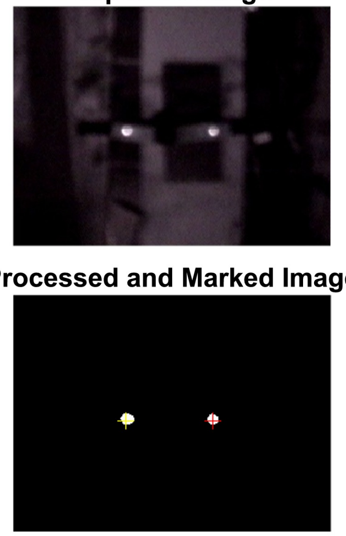

Figure 3. Output of Image Processing

second PTU, and a control computer. The camera has an infrared filter on it, and the target is tracked using fiducials that emit infrared light. This reduces the complexity of the image processing needed for the control computer. The single board control computer uses only solid state storage allowing it to function reliably despite vibrations from the helicopter. The controller uses computer vision to isolate and track the fiducials. The angle and distance to the target can be extracted using vision, and the system can then decide when conditions are optimal to perform the pickup procedure.

Visual Cargo Pickup

The visual cargo pickup algorithm is an extension of a basic visual servoing algorithm. Image processing is performed to issolate the fiducials. The effect of this processing is shown in figure 3. Crosshair markers are placed on the fiducials to indicate successful tracking. During tests, the cargo pickup system is mounted on the end effector of a gantry known as the Systems Integrated Sensor Test Rig (SISTR), described further in experimental setup. SISTR is used to replay recorded velocities from an actual helicopter flight. The cargo pickup control program then waits for the target to appear in the camera's field of view. When the fiducials appear the camera's pan tilt unit is servoed to center the fiducials in the camera's view.

Besides servoing the PTU to center the fiducials, at each iteration the program calculates the distance from the camera to the target. This calculation is based on prior knowledge of the actual distance between the fiducials and the focal length of the camera. The algorithm uses that distance and how well centered the fiducials are in the camera's field of view to determine the next step. If the target is within the range of the pickup arm and it is suitably centered in the camera's view, the pan angle of the camera's PTU is matched by the hook's PTU and the hook is swept forward towards the target. It is important that the fiducials be near the center of the camera's view to ensure moving the hook arm to the same angle as the PTU will in fact line up the arm with the target. The PTU of the hook's arm is located directly behind the camera's PTU so no additional calculations are needed to correctly match the angle of the camera. If the hook makes it through the loop of the target, and the target is lifted off the ground, then it is considered to be successfully picked up. For the purpose of future flight testing a mechanism for detection of a success pickup has been added. A wire is suspended along the top of the hook, which will flex and touch a contact when the target is hanging from the hook.

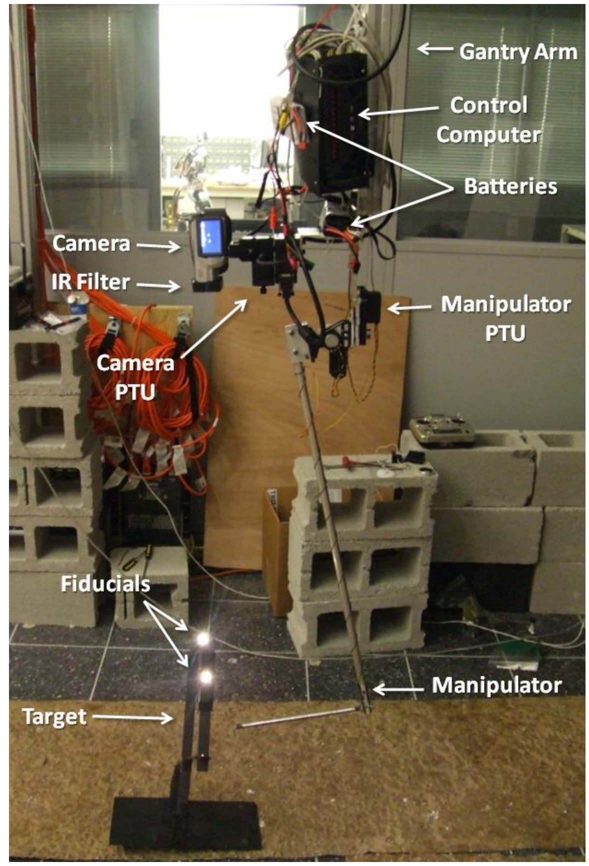

Figure 4. Cargo Pickup Mechanism

CONTROL THEORY

Visual Tracking

To track and pick up the target, a visual tracking algorithm is used. The core of the algorithm is image-based pose regulation. The pixel error between the desired position of the target and its current position is fed through a Jacobian matrix (1) that maps pixel space to Cartesian space. The goal is to reduce that error to center the target.

$$\underbrace{\begin{bmatrix}\dot{u}\\ \dot{v}\end{bmatrix}}_{\dot{s}} = \underbrace{\begin{bmatrix} -\frac{f}{z} & 0 & \frac{u}{z} & \frac{uv}{z} & -\frac{f^2+u^2}{f} & v \\ 0 & -\frac{f}{z} & \frac{v}{z} & \frac{f^2+v^2}{f} & -\frac{uv}{f} & -u \end{bmatrix}}_{L^T} \underbrace{\begin{bmatrix}T_x\\ T_y\\ T_z\\ \omega_x\\ \omega_y\\ \omega_z\end{bmatrix}}_{\vec{v}_{O'O}\vec{\omega}_{O'O}} \quad (1)$$

In equation (1) u and v represent the horizontal and vertical pixel coordinates of the target, $\dot{u}$ and $\dot{v}$ are the pixel cooridinate velocities, f is the focal length of the camera in pixels, and z is the distance to the target in centimeters. L^T is the image Jacobian. The T_x,T_y,T_z values are the translational offsets of the gantry, and the ω_x,ω_y,ω_z values are the rotational offsets. Once $\dot{u}$ and $\dot{v}$ are calculated from the image, the T value and ω values can be found by taking the pseudo inverse of L^T and performing matrix multiplication with $\dot{s}$. This sort of basic visual servoing is well established in the literature [8].

The choice of a fiducial to be visually tracked and the method of fiducial extraction were defined by two criteria: the speed at which the fiducials could be located and the ability to locate them under a variety of lighting conditions. In early tests the lighting condition constraint was ignored and standard visible LEDs were used as fiducials. The input image was thresholded and the centroids of the white regions were found. This simple method of fiducial identification allowed for ”real-time” tracking at near the speed of the video stream from the camera. Four fiducial LEDs were used for tracking the UGV, because of space constraints only two were used for tracking the loop during cargo pickup operations.

In order to satisfy the criteria of functioning under various light conditions, the fiducial was changed to one that emits infrared light, and a filter was used. Initially, infrared LEDs were tested, but had either limited viewing angle or limited brightness. The fiducials were then changed from LEDs to krypton light bulbs, which emit a significant amount of light in the infrared band. At the same time, an infrared band-pass filter was placed over the lens of the camera that was used for the vision processing. Because of the relatively poor reflectance of infrared light by most non-lustrous surfaces, even under bright lighting conditions the krypton bulbs emit far more infrared than most surfaces reflect. Figure 5 shows the effect of the filter on the acquired images and their histograms. A threshold of 170 out of 255 was used in the tests. Without the filter there is a large amount of pixels over 170 including many that are not fiducials. The addition of the filter shifts all the pixel intensities well below the threshold, except for those indicating the fiducials.

For the purposes of the initial tests the vision system

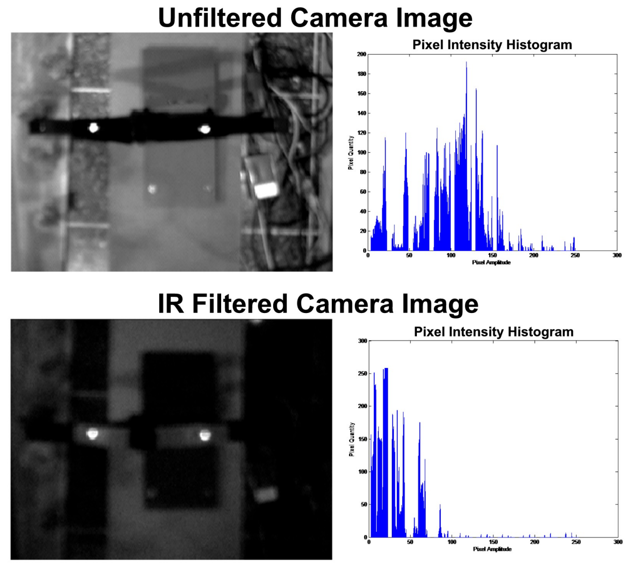

Figure 5. Effect of IR Filter on Acquired Images

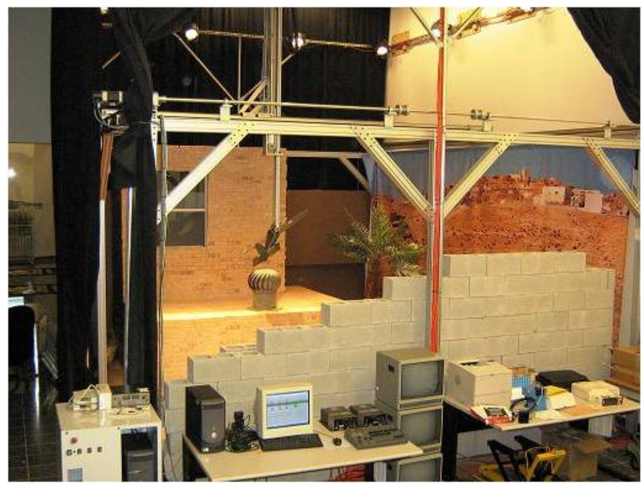

Figure 6. Systems Integrated Sensor Test Rig (SISTR)

needed to work with two backgrounds: a dark-gray asphalt parking lot, and a tan simulated-desert flooring. These backgrounds are the flying field and gantry floor, and are lit by sunlight and bright theater floodlights respectively. In both cases the light source has a significant infrared component. Preliminary video of the fiducials outdoors suggests that thresholding will be able to identify them against the parking lot surface. Extensive tests in the gantry demonstrated that tracking against the pseudo-desert flooring functioned even under the full brightness of infrared-rich theater floodlights.

EXPERIMENTAL SETUP

To develop the cargo pickup system, hardware-in-the-loop testing was used. The gantry used is known as the Systems

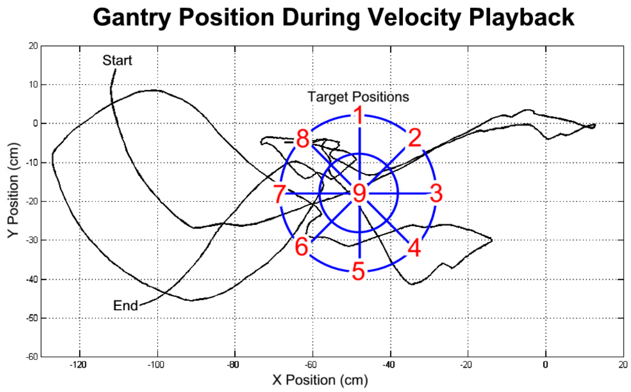

Figure 7. Graph of Gantry Position and Target Positions

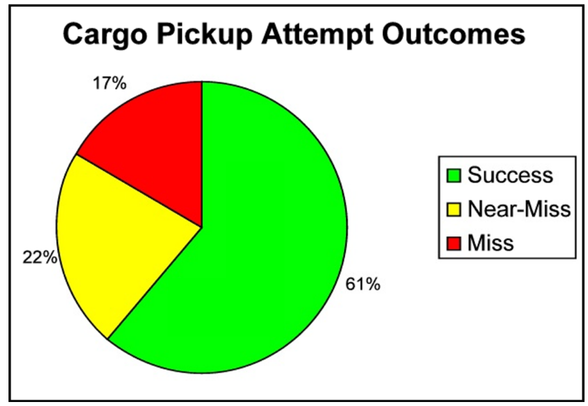

Figure 8. Graph of Visual Cargo Pickup Testing Results

Integrated Sensor Test Rig (SISTR), seen in figure 6. This is a hardware-in-the-loop testing and evaluation environment funded by the National Science Foundation (NSF) in the United States. SISTR is a 6-DOF gantry. Life size and scaled dioramas of near-earth environments like forests or urban settings can be staged inside SISTR's workspace. Lights, fans, and fog generators surrounding the workspace can generate controlled lighting, wind gusts, and obscurants like fog or smoke. SISTR's motions are controlled through model-reference adaptive control. Real-time sensor data can be fed into a high-fidelity math model of the aircraft's dynamics. The model generates motion commands that are used to update gantry motions. The net effect is a hardware-in-the-loop test rig that can rapidly and safely test and evaluate UAVs and sensor suites designed to be used in near-Earth environments. To the best of knowledge, SISTR is the only test rig of its kind documented in the public literature [9]. The cargo pickup system prototype was mounted on the end effector of this system. SISTR was then used to reproduce the velocities of the unmanned aerial vehicle. This allowed testing of the cargo pickup system under simulated flight conditions.

RESULTS

The goal of the visual cargo pickup test was to assess the reliability of the system under conditions similiar to those that would be experienced while mounted on the actual helicopter. To that end the tests were conducted with helicopter hovering velocities being played back by the gantry. This simulates the sort of motion the cargo tracking system would have to deal with on the actual aircraft. At the same time the gantry floodlights were at their full brightness, maximizing the risk of false fiducial detection and so that the environment resembled the outdoors on a sunny. When the system is mounted on the helicopter, the accuracy of the helicopter positioning is 20 cm. Because of this uncertainty, the target was placed in one central position and eight equally distributed positions in a circle of radius 20 cm. Position 9 was considered to be the actual location of the target while the other 8 positions were the possible 20 cm offsets that could occur if GPS misjudged the position in any direction. Figure 7 shows the target locations relative to the portion of helicopter data that was being replayed.

Visual cargo pickup was attempted twice for each possible position of the target, for a total of 18 tests. The results are summarized by figure 8. In 11 of the tests the target was successfully hooked by the system. During the 4 near-miss tests the hook was swung within centimeters of target's loop, contacting the outside of the loop but failing to pick up the target. The last 3 attempts either failed to swing at the target or missed completely.

The near-miss events occurred when the pickup system attempted to hook the target while the gantry was replaying a relatively high velocity. In initial tests a gear reduced pan tilt unit was used. Due to a 5:1 gear reduction on the servo PTU, it takes 1.86 seconds to move the 149 degrees of the pickup swing. The cargo pickup program determines that the target is in range and begins the swing, but during those 1.86 seconds the gantry can move out of reach of the target. This pan tilt unit was designed for power at the expense of speed. The current setup being used for ongoing tests has only a 2:1 gear reduction, reducing the swing time to approximately 0.75 seconds, which should improve the results. The processing lag for the visual control system is less than 0.1 seconds, which is believed to have a minimal amount of detrimental effect compared with the much longer servo lag.

CONCLUSION

This research has described a system for autonomous cargo transport. Through the use of hardware-in-the-loop testing, we are validating the vision system without putting an aircraft at risk. Ongoing experiments are being conducted to improve the system prior to flight tests. The visual cargo pickup system will continue to be refined using the gantry as a test bed until it can be safely deployed on a helicopter.

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