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DESIGN AND DEVELOPMENT OF AN ON-BOARD AUTONOMOUS VISUAL TRACKING SYSTEM FOR UNMANNED AERIAL VEHICLES

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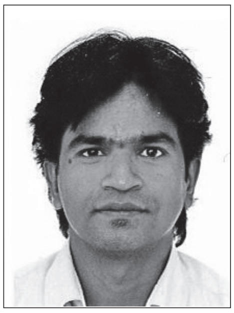

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Abstract. This paper proposes the design and development of an on-board autonomous visual tracking system (AVTS) for unmanned aerial vehicles (UAV). A prototype of the proposed system has been implemented in MATLAB/Simulink for simulation purposes. The proposed system contains GPS/INS sensors, a gimbaled camera, a multi-level autonomous visual tracking algorithm, a ground stationary target (GST) or ground moving target (GMT) state estimator, a camera control algorithm, a UAV guidance algorithm, and an autopilot. The on-board multi-level autonomous visual tracking algorithm acquires the video frames from the on-board camera and calculates the GMT pixel position in the video frame. The on-board GMT state estimator receives the GMT pixel position from the multi-level autonomous visual tracking algorithm and estimates the current position and velocity of the GMT with respect to the UAV. The on-board non-linear UAV guidance law computes the UAV heading velocity rates and sends them to the autopilot to steer the UAV in the desired path. The on-board camera control law computes the control command and sends it to the camera's gimbal controller to keep the GMT in the camera's field of view. The UAV guidance law and camera control law have been integrated for continuous tracking of the GMT. The on-board autopilot is used for controlling the UAV trajectory. The simulation of the proposed system was tested with a flight simulator and the UAV's reaction to the GMT was observed. The simulated results prove that the proposed system tracks a GST or GMT effectively.

Keywords: autonomous visual tracking system; aviator visual design simulator; cam-shift algorithm; extended Kalman filter estimator; ground moving target; ground stationary target; mean-shift algorithm; micro aerial vehicles; unmanned aircraft systems; unmanned aerial vehicles.

1. Introduction

Unmanned aircraft systems (UASs) are increasingly used for various purposes around the world. Due to the advancements in technology, large unmanned aerial vehicles (LUAVs) and small unmanned aerial vehicles (SUAVs) or micro aerial vehicles (MAVs) are being increasingly developed. LUAVs are used for military applications (Kemsaram *et al.* 2014a) such as surveillance and situational awareness. SUAVs or MAVs are used for civil applications (Kemsaram et al. 2014b) such as aerial surveillance, environmental monitoring, traffic monitoring, precision agriculture, forest and fire monitoring, and homeland security. The main advantages of UASs are their reliability at a lower cost, small size, and sufficient payload. Hence, the components of UASs also have lower payloads. Typically, LUAVs are fixed-wing aircraft with 4 to 10 feet of wing span, 10 to 50 pounds of payload, and 10 to 12 hours of operational time. These LUAVs use a catapult for take-off and a skyhook for recovery. SUAVs or MAVs are fixed-wing aircraft with less than 5 feet of wing span, less than 10 pounds of payload and up to a couple of hours of operational time. These SUAVs do not require a runway, catapult or skyhook for take-off and recovery, since they are typically battery powered, hand launched, and belly landed. A radar has been used as the prime source of surveillance for GMT tracking; however, the on-board camera of an SUAV can also be utilized for GMT tracking purposes. The position and velocity of a GMT can be obtained by processing a real-time GMT video. These parameters can be used for the computation of the SUAV guidance law. Afterwards, the autopilot will receive a computed guidance command

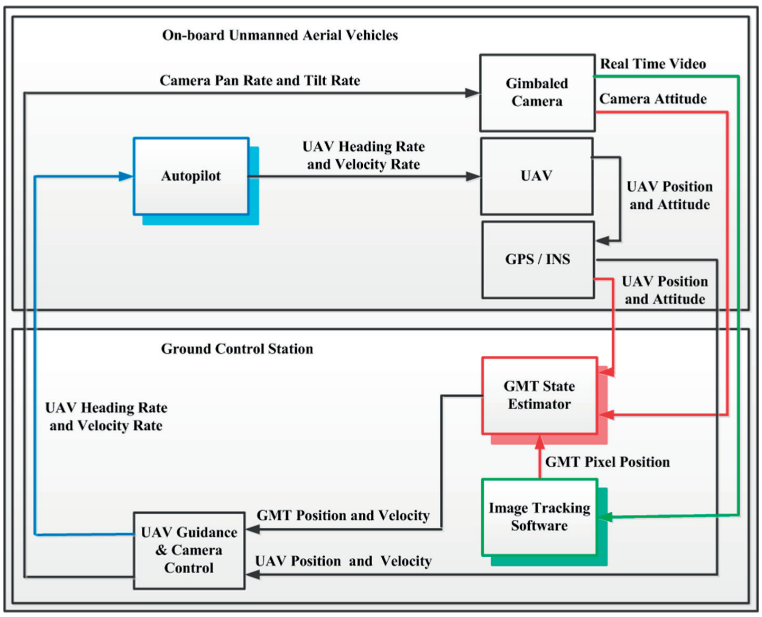

Fig. 1. Architecture of an existing AVTS (an AVTS controlled by a GCS)

and will steer the SUAV in the desired path. The existing AVTS is controlled by the ground control station (GCS), which receives the video frames from the on-board SUAV camera and where an operator can analyze and send the guidance commands to the SUAV via an RF link in order to track the GMT continuously (Prince 2004; Beard *et al*. 2005; Tay 2006; Theodorakopoulos, Lacroix 2008; El-Kalubi *et al*. 2011; Regina 2011; Qadir *et al*. 2011; Xin *et al*. 2011; Peliti *et al*. 2012; Wang *et al*. 2014; Chuan 2009). Manual visual tracking software requires a lot of time for the communication between the operator and the SUAV. Hence, an on-board AVTS, which would receive the video frames from the on-board SUAV camera and would contain an efficient multi-level autonomous visual tracking algorithm based on image processing (Kemsaram *et al.* 2017), is needed to guide the SUAV and to control the camera for tracking the GMT continuously. The main objective is to design and develop an efficient on-board AVTS for SUAVs.

2. Methodology

In this section, the existing methodology for an AVTS is described in more detail. Figure 1 shows the architecture of an AVTS which is controlled by a GCS and consists of GPS and INS sensors, a gimbaled camera, image tracking software (Kemsaram *et al.* 2015, 2016a, 2016b, 2016c, 2016d), a GMT state estimator (El-Kalubi *et al*. 2011), a UAV guidance law (El-Kalubi *et al*. 2011), a camera control law (El-Kalubi *et al*. 2011), and an autopilot (El-Kalubi *et al*. 2011).

2.1. GPS and INS sensors

On-board GPS and INS sensors provide the UAV position and attitude to the ground-based GMT state estimator for the computation of the GMT bearing.

2.2. Gimbaled camera

An on-board pan-tilt camera mounted on a gimbaled controller sends the video frames to the ground-based image tracking software through an RF link. Based on the pan and tilt rates provided by the ground-based guidance/control law computer, the gimbaled camera can perform a pan and tilt motion (Xin *et al*. 2011).

2.3. Image tracking software

The ground-based software image tracking software receives the video frames from the on-board camera through the RF link. It provides a graphical user interface (GUI) for the selection of the GMT in the real-time video. The user can select the desired GMT using a computer mouse/joystick. This software contains the mean-shift algorithm (Comaniciu, Meer 1999, 2002; Comaniciu *et al*. 2000; Paris, Durand 2007), the cam-shift algorithm (Comaniciu *et al.* 2003; Intel 2010), the Extended Kalman Filter (EKF) estimator (Kalman 1960; Kalman, Bucy 1961; Welch, Bishop 2001; Janabi, Marey 2010) or the hybrid algorithm (Abhari *et al*. 2011; Salhi, Jammoussi 2012; Kemsaram *et al.* 2015, 2016a, 2016b, 2016c, 2016d), which compute the pixel position of the centroid of the selected GMT.

2.4. GMT state estimator

The GMT state estimator, which is also a ground-based system, receives the pixel position from the image tracking software. The GMT centroid pixel information, UAV position, UAV attitude, and camera attitude are used to compute the GMT bearing. The GMT bearing angle rate is used in the estimation of the GMT position and velocity (Zhang, Liu 2010; Dobrokhodov *et al*. 2006; Li *et al*. 2010).

2.5. UAV guidance

The ground-based system for UAV guidance computes the guidance command for the UAV motion (Wang *et al*. 2014; Peliti *et al*. 2012), which is then sent to the autopilot through the RF link.

2.6. Camera control

The ground-based system for camera control computes the control command for the camera's pan-tilt control (Cohen, Medioni 1998; Yau *et al*. 2001). The computed command is then sent to the autopilot or the gimbaled camera controller via the RF link.

2.7. Autopilot

The autopilot is an on-board system which is used for controlling the trajectory of the UAV. It receives the the heading and velocity rates from the UAV guidance law computer through the RF link and steers the UAV in the desired trajectory (Chao *et al*. 2007).

The main drawbacks of the existing methodology are:

- the radar weight constraint, since it is not feasible to put a radar in a UAV;
- the high cost of the radar for surveillance and GMT tracking;
- longer time required for the operator to perform the operations and requirements;
- on-ground image tracking software controlled by the GCS;
- difficulties in detecting when a GMT moves out of the frame or is not visible due to occlusions.

To overcome the drawbacks listed above, an efficient multi-level autonomous visual tracking algorithm (Kemsaram *et al.* 2017) is included in an on-board AVTS for GMT tracking.

3. Proposed methodology

This section explains the proposed methodology for an on-board AVTS in greater detail. Our aim for the on-board AVTS design is to develop and demonstrate the ability of autonomous GMT tracking from a UAV. It assumed that the inertial frame center at the origin, the UAV body frame at UAV itself, and the on-board gimbaled camera frame at the UAV. The on-board gimbaled camera frame rotates with respect to the UAV body frame. The Z-axis of the camera aligns with the GMT via the line-of-sight (LOS).

Vector P_{GMT} is the GMT position in the inertial frame, P_{UAV} is the UAV position in the inertial frame, and P is the GMT relative position to the UAV.

The relation between these vectors is as follows:

$$P_{GMT} = P_{UAV} + P. \tag{1}$$

Vector P_{UAV} is the UAV position, provided by the on-board INS/GPS sensors.

Vector P is the GMT relative position to the UAV, computed by the following equation:

$$P = R_B^I R_C^B P_C, \tag{2}$$

where R_B^I and R_C^B are the transformation matrices for the transformation from the UAV body frame to the inertial frame, and from the gimbaled camera frame to the UAV body frame, respectively.

Vector P_C is the GMT position from the UAV in the gimbaled camera frame, provided by the multi-level autonomous visual tracking algorithm.

Afterwards, Equation 2 is substituted in Equation 1,

$$P_{GMT} = P_{UAV} + R_B^I R_C^B P_C. \tag{3}$$

The GMT position information, P_{GMT}, is used in the GMT state estimator.

The estimated GMT position and GMT velocity are used for the UAV guidance law and camera control law, which are required for the continuous tracking of the GMT autonomously.

The main objectives for the development of an on-board AVTS are as follows:

– a multi-level autonomous visual tracking algorithm;
– a GMT state estimator;
– a UAV guidance law;
– a camera control law.

The proposed methodology for the on-board AVTS architecture, which consists of on-board GPS/INS sensors, a gimbaled camera, a multi-level autonomous visual tracking algorithm, a GMT state estimator, a UAV guidance law, a camera control law, and an autopilot, is described in the following sections and is shown in Figure 2.

3.1. GPS and INS sensors

The on-board GPS and INS sensors provide the UAV position and attitude. This information is used by the on-board GMT state estimator for the computation of the GMT position and velocity.

3.2. Gimbaled camera

The on-board camera mounted on a gimbaled controller provides a real-time video. This camera can perform a pan and tilt motion, based on the pan and tilt rates provided by the on-board camera control law.

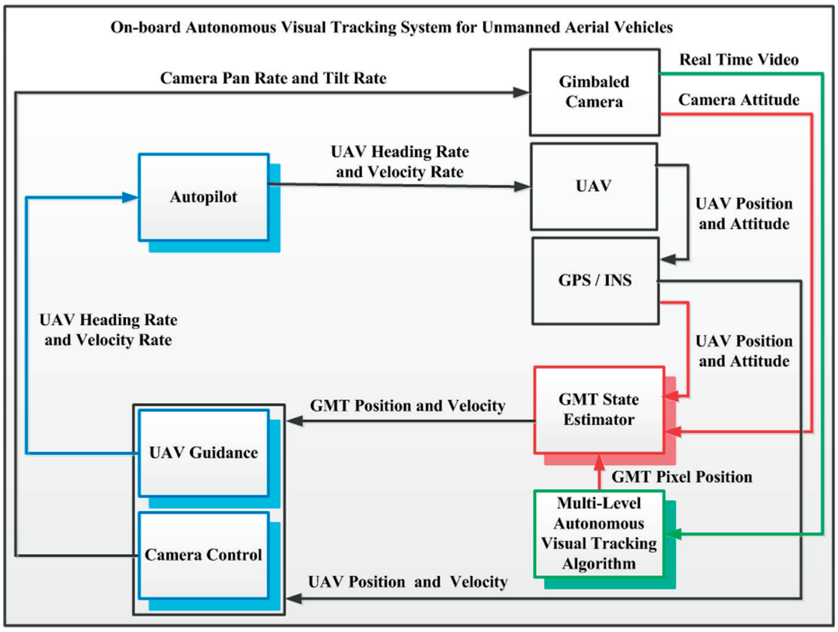

Fig. 2. Proposed architecture for an on-board AVTS (AVTS controlled by the on-board multi-level autonomous visual tracking algorithm)

3.3. Multi-level autonomous visual tracking algorithm

The on-board multi-level autonomous visual tracking algorithm (Kemsaram *et al.* 2017) is based on the mean-shift, cam-shift, and the EKF. It estimates the GMT path and computes the pixel position of the GMT centroid in the image.

3.4. GMT state estimator

The on-board GMT state estimator is based on the EKF estimator, which receives the GMT pixel position from the multi-level autonomous visual tracking algorithm. The GMT pixel information, UAV position, velocity, and attitude as well as the attitude of the camera are used for the computation of the current position and velocity of the GMT with respect to the UAV.

3.5. UAV guidance law

An on-board non-linear UAV guidance law, which computes the UAV's heading and velocity rates and is based on the Lyapunov Vector Filed Guidance method, has been developed. The computed command is sent to the autopilot to steer the UAV in the desired direction.

3.6. Camera control law

An on-board non-linear camera control law has been developed to compute the pan and tilt rates for the control command of the camera. The computed command is sent to the gimbaled camera controller to keep the GMT in the camera's field of view.

3.7. Autopilot

An on-board autopilot, which is used for controlling the trajectory of the UAV, has been developed,. It receives the UAV's heading and velocity rates from the UAV guidance law. The computed control command is sent to the UAV to steer it along the desired trajectory.

4. Simulation implementation and results

A MATLAB/Simulink simulation model has been created to simulate the gimbaled camera control (Garcia 2012), camera model (Wang 2011), UAV model (Al-Radaideh *et al.* 2009; Al-Radaideh 2009), GMT model (El-Kalubi *et al.* 2011), and autopilot (Mandrekar 2008; Athulathmudali 2008; Saban 2006; Qureshi 2008) in order to check if the control algorithm meets the requirements for a multi-level autonomous visual tracking algorithm. The mathematical models of the GMT model (El-Kalubi *et al.* 2011), pinhole camera model (Brake 2012), GMT state estimator (Quek 2005), 6DOF UAV model (Watkiss 1994), camera control law (Garcia 2012), UAV guidance law (Chuan 2009), and autopilot (Johansen 2012; Christiansen 2004) have been developed and are shown in Figure 3.

We have designed a realistic Simulink model to simulate the following test cases and have observed the reactions of the multi-level autonomous visual tracking algorithm and the gimbaled pan-tilt camera as well as the UAV's motion.

In the first test case (Test Case 1), a moving UAV with a camera, moving over the GST and GMT, was analyzed. The simulated GST and GMT are on the ground, and the UAV starts with a straight and level flight at an altitude of 1000 m above the GST and GMT with the UAV velocity at 25 m/s. The specified UAV altitude is 1500 m, the heading is north (0^0), and the standoff radius is 100 m. This duration of the test was 60 seconds. It was observed that the UAV achieved its commanded altitude, 1500 m, and flew in circles around the GST and GMT with a standoff radius of 100 m.

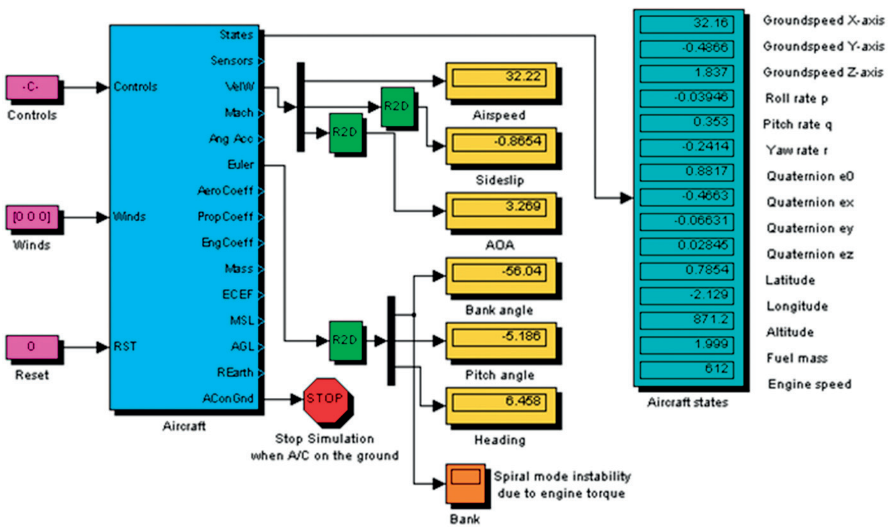

Fig. 3. Simulation – an open loop Simulink model

Figure 4 shows UAV trajectory circles over a GST (2D).

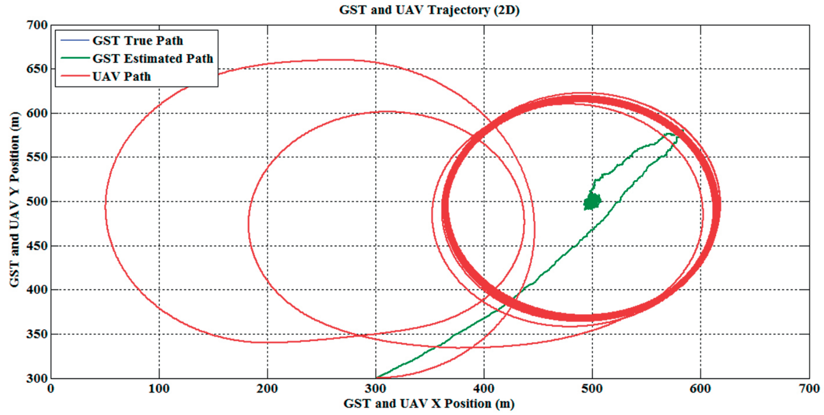

Fig. 4. UAV trajectory circles over a GST (2D)

Figure 5 shows UAV trajectory circles over a GST (3D).

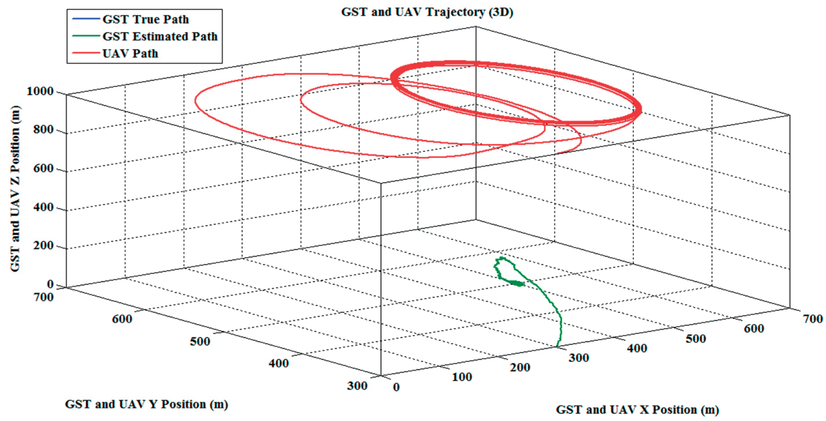

Fig. 5. UAV trajectory circles over a GST (3D)

Figure 6 shows UAV trajectory circles over a GMT (2D).

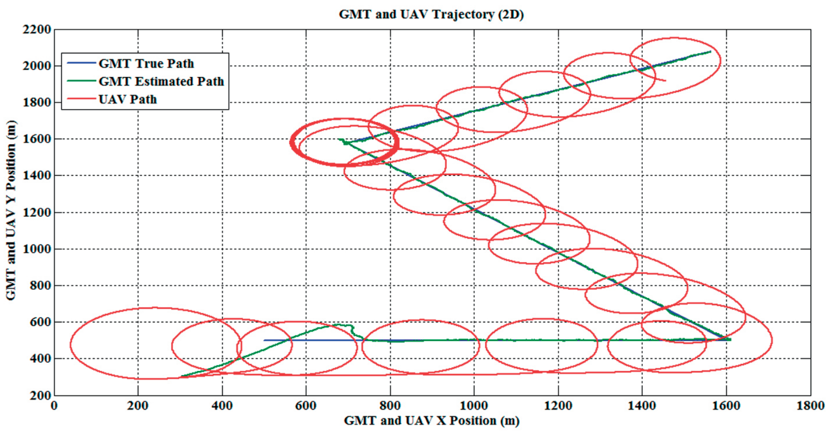

Fig. 6. UAV trajectory circles over a GMT (2D)

Figure 7 shows UAV trajectory circles over a GMT (3D).

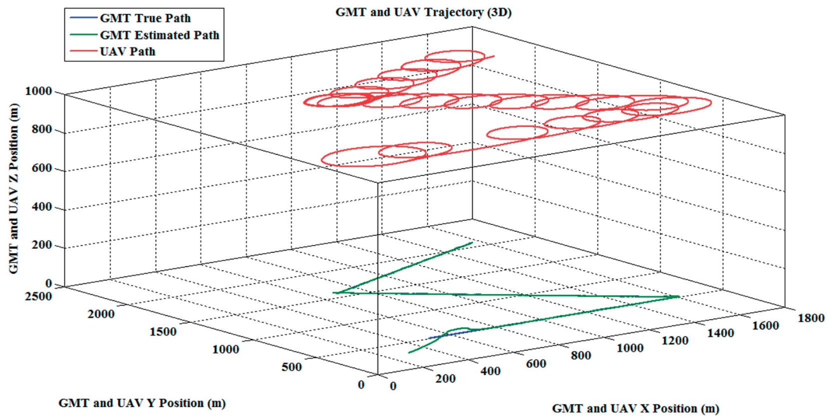

Fig. 7. UAV trajectory circles over a GMT (3D)

Test Case 2 involved closed loop testing with a flight simulator. After testing the on-board AVTS within Simulink, the next step was to incorporate the majority of the hardware into the testing process. This included incorporating the multi-level autonomous visual tracking algorithm and using the output to drive the on-board AVTS. In order to incorporate the multi-level autonomous visual tracking algorithm, it was necessary to create video images of the GMT in the camera frame. To do this, an Aviator Visual Design Simulator (AVDS) is used, which is a software program developed by RasSimTech Ltd (AVDS 2016) that interfaces with Simulink and provides a visual representation of a UAV in flight. It allows customizing the terrain, so it was possible to add a GST on the ground. Based on the camera's position and orientation, it was possible to get a simulated camera view and send the output to the multi-level autonomous visual tracking algorithm. The algorithm was then able to identify and estimate the GMT path within the image plane as well as to send the error values back to the on-board AVTS. FlightGear (FlightGear 2016) was chosen to drive the 3D visualization, because it is a freeware software tool that can be easily connected to MATLAB/Simulink and has a lot of scenery to make the 3D visualization more realistic.

Conclusions

An on-board AVTS for UAVs is proposed. A prototype of the proposed system has been created in MATLAB/Simulink for simulation purposes. The simulation of the proposed system has been tested with a flight simulator and the reaction of the UAVs and GMTs has been observed. The simulated results prove that the proposed system is able to track the GST or GMT autonomously.

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