

An Augmented Reality System for Multi-UAV Missions

Ali Haydar GÖKTOĞAN, Salah SUKKARIEH

ARC Centre of Excellence for Autonomous Systems

Australian Centre for Field Robotics

School of Aerospace, Mechanical, and Mechatronic Engineering

University of Sydney, NSW Australia

{agoktogan,salah}@acfr.usyd.edu.au

Abstract. *Augmented Reality* (AR) is a relatively new field of research with diverse application areas. In this paper we present a novel approach in using AR technology in multiple *Unmanned Air Vehicle* (UAV) missions to augment the UAVs' sensor systems with *Decentralised Data Fusion* (DDF) capable sensors, performing multi-modal sensor registration and cooperative control experiments. The AR system is being developed in our *Real-time Multi-UAV Simulator* (RMUS). RMUS has been used for many multi-UAV simulations and also in real flight trials as a mission control system. The AR system allows us to execute multi-UAV missions in which the real and simulated UAVs and other heterogeneous agents interact with each other in real-time.

1. INTRODUCTION

Augmented Reality (AR) is a relatively new field of research with diverse application areas. Robot path planning [1], medical training [2], air traffic control [3] are just a few example of the AR. A survey of AR system can be found in [4]. In the majority of the AR related publications, augmentation of the human audio and vision sensory systems is the main focus. In this paper, however, we present a novel approach to use AR technology in multiple *Unmanned Air Vehicle* (UAV) missions to augment the UAVs' sensor systems.

Use of UAVs, as robotic platforms, is gaining more popularity in the robotics research community. UAVs are inherently difficult platforms to work on. They are expensive and high risk platforms for academic research projects with limited budget. UAVs require specialised infrastructure for their maintenance and operations. The operational infrastructure has to be supported by a variety of highly qualified technical personnel. Due to civil aviation, health and safety regulations, UAV operational space is restricted to relatively remote sites. UAV operations require mastery in logistics. Operational complexity increases substantially when missions require simultaneous flights of multiple UAVs.

Therefore, understandably, the research activities, requiring the operation of multiple UAVs are mostly limited with low fidelity, simulation only trials [5, 6, 7].

There are also research and development works performed successfully both in high fidelity simulations as well as on multiple real UAVs. At the *Australian Centre for Field Robotics* (ACFR) we have performed numerous single and multi-UAV missions with the Brumby Mk III UAVs. In these missions, airborne application of the *Decentralised Data Fusion* (DDF), *Simultaneous Localisation And Mapping* (SLAM) and picture compilation algorithms has been successfully demonstrated [8].

This paper presents the major roles of the AR system on multi-UAV missions. The presented AR system is being implemented in the *Real-time Multi-UAV Simulator* (RMUS) that is developed at the ACFR [9]. RMUS has been used for many multi-UAV simulations and also in real flight trials as a mission control system.

The AR system allows us to execute multi-UAV missions in which the real and simulated virtual UAVs and other heterogeneous agents interact with each other in real-time. Also the real UAVs can be equipped both with real and/or virtual sensors.

This paper is organized as follows: the next section presents the proposed AR system. Section 3 presents the UAV platform used in our experiments. In Section 4 the sensor model, sensor node structure and applications of the AR system are introduced. Finally, conclusion, further works are provided.

2. AUGMENTED REALITY

2.1 Definition

The definition of the term “Augmented Reality” (AR), is revised continuously as new applications emerge. It is hard to find what could be reasonably considered and consistent definition of an AR system. The concepts of AR, *Mixed Reality* (MR) [10], *Shared Reality* (SR) [11], and *Virtual Reality* (VR) systems are closely related and overlap with each other with fuzzy boundaries.

Rather than elaborate on the continuum of definitions from AR to VR systems, we simply define the function of an AR system as “augmenting the perception of a sensory system to provide additional information that can not be acquired directly by that sensory system itself”.

2.2 The AR system architecture

In the context of this paper, the AR system refers to being able to augment, in real-time, the perception of

the world as seen by the sensors with DDF capability, carried on multiple UAVs.

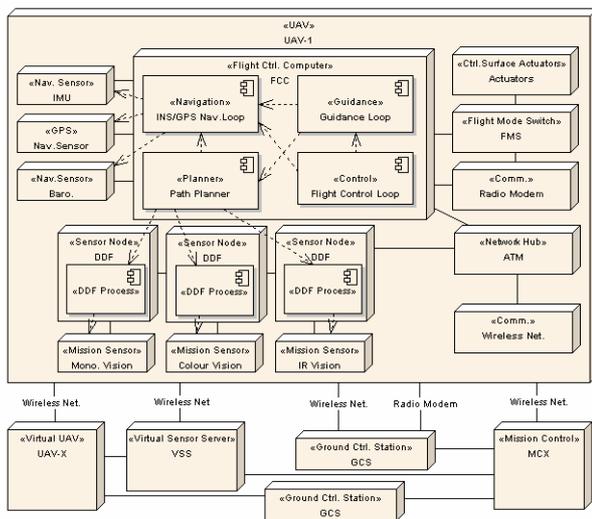


Figure 1: A simplified deployment diagram of the AR system.

The augmentation is performed in such a way that both the real and virtual vehicles can be equipped with virtual sensors. These sensors can interact with the virtual objects, such as virtual targets and virtual UAVs in the synthetic environment representing the operation space.

Figure 1 shows a simplified version of the deployment diagram of the AR system used in the multi-UAV missions. The deployment diagram blocks are described as follows;

- **UAV** - The main block UAV-1, contains four computers; the *Flight Control Computer* (FCC) and three DDF computers. The FCC runs the INS/GPS navigation loop, the guidance loop and the flight control loop (autopilot). Depending on the mission, it may also run a high level path planning algorithm. Figure 1 also shows a virtual UAV (UAV-X). In terms of computing and communication hardware, the virtual UAV is identical to the real UAV (UAV-1), but the UAV-X is abstracted into a single block to minimise clutter in the diagram. The mission sensors on the virtual UAV can only perform observations in the augmented virtual world in the synthetic environment.

- **Navigation Sensors** - The navigation sensors; IMU, GPS and barometric pressure sensor are connected to the FCC computer. The navigation component fuses the INS/GPS and barometric sensor data to generate navigation solution. All the other components that run on the FCC and on the sensor nodes, use the navigation solution. These dependencies are represented by the dashed arrows in Figure 1.

- **Mission Sensors** - Each mission sensor has its own computer to run the DDF code. The sensor nodes and the FCC are networked together by a network hub. The mission sensor architecture has been further described in Section 4.

- **Flight Mode Switch** - The UAVs are being operated under the control of either remotely by a human pilot or an autopilot and the guidance systems running in the FCC. The switching between the remote control to the fully autonomous mode is performed by the *Flight Mode Switch* (FMS). The FMS is an embedded controller board, and it also continuously monitors the communication between the UAV and its GCS. In case of a fatal communication failure, the FMS instructs the FCC to initiate predefined emergency operational procedures to guaranty the safety of the mission.

- **Ground Control Station** - Each UAV, regardless if it is real or virtual, has its own *Ground Control Station* (GCS) computer. The UAV's internal network is partially accessible from the GCS computer via the wireless network. The GCS is used to monitor and control its associated UAV. The GCS also connected to a long range radio modem for remote piloting of the UAV.

- **Mission Control Station** - The UAV missions are monitored and controlled by the *Mission Control* (MCX) computer. The MCX displays real and virtual UAV positions, sensor frustums and mission data, including DDF results, and the 3D terrain of the operation space. The MCX and the GCS computers are connected to the same LAN. The MCX is also networked, via wireless network, with the UAVs (both real and virtual), thus, it can access the DDF network.

- **Virtual Sensor Server** - The virtual sensors observe the augmented world; the world consists of simulated instances of the real UAVs and other virtual objects in the synthetic environment. The virtual sensors are realised through the *Virtual Sensor Server* (VSS) in which the high fidelity sensor simulation models are being executed. The VSS receives the *Position, Velocity, Acceleration* (PVA) data from UAVs. Given the position and attitude of the virtual sensors with respect to the UAV, it interact with the augmented world to generate observations.

- **Communication** - The Brumby Mk III UAVs carry two types of communication hardware; a long range full-duplex spread spectrum radio modems and an IEEE 802.11 wireless networking unit with enhanced range capability.

The radio modems are used for remote piloting commands, system health and status messages communicated between ground control stations and the UAVs. The wireless network offers wider bandwidth for either raw sensor data or DDF information and/or any negotiation protocol packages required for co-operative control algorithm. The wireless network is used between UAV to UAV and ground to UAV communications.

2.3 Augmented World

For the real entities, such as real UAVs, the augmented world refers to the real world observed by its sensors and enhanced by the virtual observation it receives from the AR system. For the virtual entities, the augmented world consists of the 3D terrain of the operational space, simulated vehicles, stationary and/or moving targets and the live-virtual copy of the real UAVs, all created in the synthetic environment. In this environment, the PVA data received from the GCSs of the real UAVs are linked to the simulated UAV models. As the real UAVs manoeuvre in the real 3D world, the simulated UAVs corresponding to the real ones manoeuvre in the synthetic 3D world.

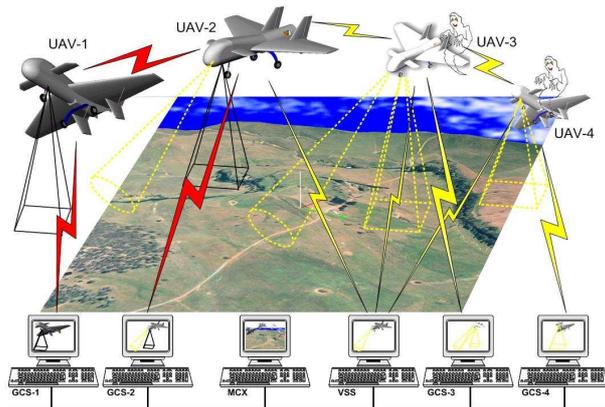


Figure 2: An AR system configuration used in multi-UAV missions.

The augmented world is generated in the RMUS which supports distribution of complex simulations over a number of networked computers. The RMUS provides real-time, high fidelity simulation models of the flight vehicle dynamics. The virtual UAVs which are created through the script code can be linked with these models to generate real-time, realistic flight trajectories. RMUS also provide logging and replay functionality of the whole mission. The real UAV flights can be replayed in RMUS with different AR configurations [9].

Figure 2 shows an AR system configuration to be used in multi-UAV missions with four UAVs. In this configuration, UAV-1 and UAV-2 represent the real UAVs while UAV-3 and UAV-4 represent the virtual UAVs. The real and the virtual UAVs interact with each other. The real UAV-2 is also equipped with one real and one virtual sensor, where the frustum with solid lines represents the real sensor and one with the dashed line represents the virtual sensor.

3. UAV SYSTEMS

3.1 Brumby Mk III UAV

We use the Brumby Mk III UAVs in our research experiments. The Brumby Mk III UAVs are delta wing aircraft with pusher type propeller. The Figure 3 shows the Brumby Mk III UAV fleet used by the ACFR. They are designed and manufactured at the University of

Sydney, primarily as research platform for the field robotics applications. The Brumby UAVs have conventional tricycle undercarriage suitable to be operated on the short grass and the asphalt surfaces for take-off and landing.



Figure 3: The Brumby Mk III UAV fleet used for single and multi-UAV missions.

Over the years, as a result of increasing payload weight demand for the new research projects, the Brumby UAVs have incorporated a number of changes. The current version of the UAV, the Brumby Mk III, is capable of carrying approximately 13 kg payload with 1 hour worth of fuel.

3.2 Mission Sensors

The Brumby Mk III UAV is capable of carrying a variety of payload sensors and mission sensors. Payload sensors consist of an *Inertial Navigation System* (INS), a *Global Positioning System* (GPS), and a barometric pressure sensor. The mission sensors are monochrome, colour and Infrared (IR) vision sensors, *Secondary Imaging System* (SIS) which is a vision system improved with laser range finder, and *Millimetre Wave* (MMW) Radar.

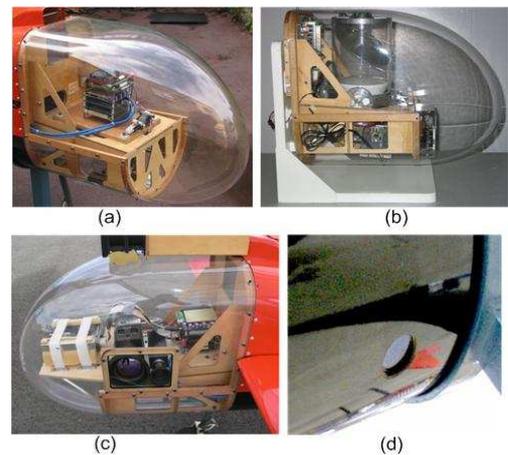


Figure 4: The replaceable nose cone of the Brumby Mk III UAVs is used to attach either (a) an SIS or (b) MMW radar or (c) colour and IR camera. The (d) monochrome vision camera.

The monochrome vision camera is fixed to the fuselage in downward looking configuration. Other mission sensors are located in the replaceable nose cone as shown in Figure 4.

Only one sensor can be placed in the replaceable nose cone (with the exception of the colour and the IR sensors which are placed together in the same nosecone). This limits the possible combinations of sensors to be carried on board and consequently limits the variety of experiment; especially those require multi-modal sensor data. Through the VSS, the proposed AR system provides an answer to this problem by allowing placement of virtual sensors to the real UAVs.

4. SENSOR NODES

4.1 Sensor Model

The VSS uses various sensor models to simulate the sensor returns [12, 13]. Simulated sensors interact with the virtual entities in the augmented world. The observations made by the sensors are transformed into a common reference frame, called the earth frame as shown in Figure 5-a. Given the relative position and attitude of the vehicle (Figure 5-b) and the location of the sensor payloads relative to the vehicle (Figure 5-c, d), and the sensor model characteristics (Figure 5-e, h), the position of the target in an observation can be calculated in the earth frame.

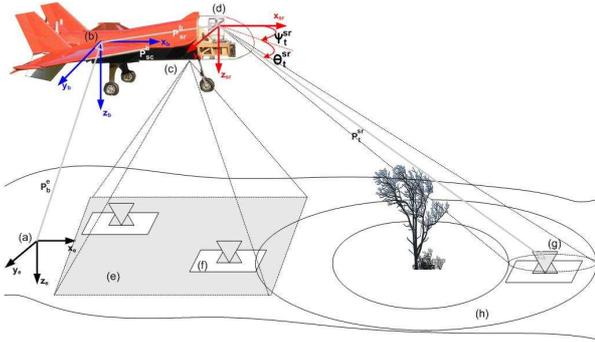


Figure 5: The graphical representation of the coordinate systems. The (a) earth frame, (b) body frame, (c) camera sensor frame, (d) the Radar sensor frame, (e) camera frustum, (f) vision target, (g) Radar target, (h) Radar scan pattern.

Due to the limited page count for the paper, we only formulise the transformation for the nose cone mounted scanning radar sensor. For a target t detected by the sensor sr , on a UAV body frame b , the observed position of the target is transformed to the earth frame e as follow;

$$P_t^e = P_b^e + C_b^e P_{sr}^b + C_b^e C_{sr}^b P_t^{sr} \quad (1)$$

where P_{f1}^{f2} is position of the $f1$ in the frame $f2$ and C_{f1}^{f2} is the direction cosine matrix defines the rotation of the frame $f1$ with respect to the frame $f2$.

$$P_t^{sr} = \begin{bmatrix} r_t^{sr} \cos \theta_t^{sr} \cos \psi_t^{sr} \\ r_t^{sr} \cos \theta_t^{sr} \sin \psi_t^{sr} \\ r_t^{sr} \sin \theta_t^{sr} \end{bmatrix} \quad (2)$$

Equation 2 defines the position of the target in the sensor frame P_t^{sr} is defined by the grazing angle θ_t^{sr} , the azimuth ψ_t^{sr} , and the range of the target r_t^{sr} .

4.2 Sensor Node Architecture

In the context of this paper, the data fusion refers to estimation of the states of the augmented world through a mixture of information obtained from real and virtual sensors.

In a DDF network each sensor is associated with a processing unit called the sensor/fusion node. Each node executes its own local estimation code and broadcast its results to other nodes through its channel filter. After each communication and fusion process cycle, each node reconstructs the global information state of the augmented world model [8].

The DDF systems can be characterized by three properties [14];

- There is no single central fusion centre and no node should be central to the operation of the network
- There is no common communications facility - communications must be kept on a strictly node-to-node basis
- Each node has knowledge only of its immediate neighbours - there is no global knowledge of the network topology.

Unlike the centralised fusion systems, the DDF systems continue functioning even after failure of any node or communication link on its network. The result of such a failure is a gradual degradation in network performance rather than total failure of the whole system [15].

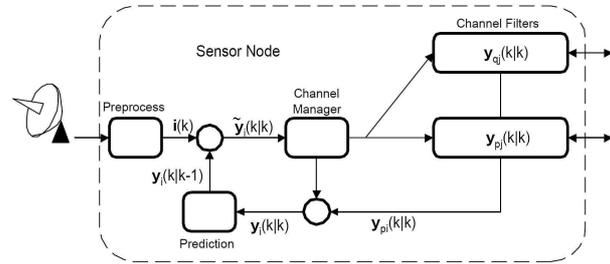


Figure 6: The architecture of a decentralized data fusion node.

The sensor node architecture is illustrated in Figure 6. The pre-processor performs feature extraction on the raw sensor data and transform the observation data into the information form to be fused in the local filter. Based on observed, predicted and communicated information, the local filter calculates information state

estimates. The channel filters keep track of the communicated information. The information gain is calculated based on the previously communicated information. Sensor nodes communicate with each other via channel filters. The channel filters are linked to the local filter through the channel manager.

Further details of the decentralized data fusion process are beyond the scope of this paper. A comprehensive coverage of the DDF applications in airborne sensor networks can be found in [8, 14, 15, 16].

In The Brumby Mk III UAVs, each mission sensor node has its own PC104+ computer with Pentium processor for data acquisition, pre-processing and data fusion. The PC104+ hardware is compatible with the desktop computers. The same DDF software that runs on the PC104+ can also be used on the desktop computers. Thus, the desktop computers can be configured as virtual sensor nodes in the AR system and can be integrated to the data fusion networks as if they were real sensor nodes.

4.3 Virtual Observations

Depending on the communication bandwidth available in a particular AR system configuration, the virtual sensor observation, generated in the VSS can be used in two main forms;

- If the system has enough bandwidth, the raw sensor data from the virtual sensor can be transmitted to the DDF node on the UAV. This sensor data is fed into the pre-processor of the DDF node for the feature extraction followed by the fusion processes.
- If bandwidth is limited, then an instance of the DDF node should be created on the VSS computer. Thus, the raw sensor data from the high fidelity sensor model can be linked directly to the pre-processor of the DDF node without affecting the network traffic. Compared to the raw observations, the information from the channel filter output of the DDF node requires less bandwidth. The information vector $i(k)$ and the information matrix $I(k)$ then can be transmitted to the rest of DDF network.

For a sensor node with the DDF capability, there is no difference if the information is sent from a real or virtual sensor node.

4.4 Applications of the AR System

The ultimate goal of the proposed AR system is to demonstrate it in multi-UAV missions in which a DDF network is created between real and virtual sensors carried on real and virtual vehicles.

A typical application of such a system is the co-operative control of a team of heterogeneous UAVs performing target detection and tracking. The target detection and identification process requires observation

of the probable target locations with a set of sensors to acquire multi-spectral data. Especially in operations with the small sized UAVs, which a single UAV is not capable of carrying multiple sensors, a team of UAVs with different types of sensors has to visit the area of interest. Demonstration of the co-operative control techniques on multiple UAVs with many real sensors requires more resource than what currently we have. This situation was the opportunity to develop and demonstrate the AR system, in which we will be able to equip the real UAVs with virtual sensors and create multi-UAV missions where real UAVs will cooperate with multiple virtual UAVs in real-time.

The current research activities at the ACFR, includes development of various co-operative control algorithms for a team of UAVs [17, 18, 19]. Once new project opportunities arise to deploy these algorithms on the real vehicles, considering the limited resources of the real UAVs available, they will be demonstrated in the AR system with a minimum number of real UAVs co-operating with a larger number of virtual UAVs.



Figure 7: A screen shot from an airborne Vision Sensor Detection Performance Simulation (VSDPSim) performed in the RMUS.

We have also developed an airborne *Vision Sensor Detection Performance Simulation (VSDPSim)* on the RMUS environment to assess sensor readings [13]. Figure 7, show a screen from the VDPSim.

The VSDPSim has been tested both in simulation only trials and also in a remotely piloted single-UAV flight mission. Demonstration of autonomous, single-UAV, multi-sensor and multi-UAV, multi-sensor missions are scheduled for May 2005.

5. CONCLUSION AND FURTHER WORKS

This paper presented an AR system architecture to be used on multi-UAV missions. The presented AR system is still being under development. The current version of the AR system has been tested with the RMUS environment with successful results.

The multi-UAV system that is built and operated successfully by the ACFR is also presented. The proposed AR system will be used to extend the capabilities of our existing UAV fleet.

As a part of continuous system improvement and extending process, we are also working on the development of *A Framework for Decentralised Autonomous Systems* (AFDAS). The AFDAS will support existing multi-UAV system architecture and the proposed AR system. Furthermore, the work is on progress for the High Level Architecture (HLA) compliance of the RMUS and the AR system, for interfacing with the third party software.

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