A Review of Autonomous Docking Technologies for an Unmanned Aircraft Carrier

Y. Guo & S.D. Prior
Computational Engineering Design Research Group
Aeronautics, Astronautics and Computational Engineering Design Faculty of Engineering and the Environment
University of Southampton

ABSTRACT: Aerial carrier is becoming a hotspot in Remote Piloted Aircraft System (RPAS) research area recently. As a variant of the general RPAS swarm, this technology is believed to be promising in both military and civilian applications. For example, it could enhance the safety of a military surveillance mission, it could enlarge the surveillance region coverage and it could extend the communication range of any single RPAS. One essential problem for the realisation of the aerial carrier is the autonomous docking in the air. This paper presents a review of autonomous docking techniques ranging from active LED recognition to passive laser scanning and three-dimensional (3D) remodelling. It is aimed at providing a broad perspective on the statues of the recognition and position estimation problems.

1 INTRODUCTION

1.1 *Why Aerial Carrier*

Small Remotely Piloted Aircraft System (RPAS) is currently under increasingly fast development. Due to the features of small-size, small-mass (< 2 kg), low-cost, low-risk and high-agility, they have become powerful competitors to conventional manned aircraft in both military and civilian applications. However, these features also greatly limited the endurance and the communication range compared with manned aircraft. Under this background, the concept of Aerial Carrier for RPAS has been proposed (Atherton, 2014). This concept is believed to be able to combine the benefits of small RPAS with the speed, endurance and range of large carriers.

1.2 *Brief history of Aerial Carrier*

Aerial Carrier is not a new idea though. In early 1930s, the US Naval has faced the similar problem. The small bi-plane used for scouting had very limited range compared to the oceans needed to be watched. The 1000-foot-long airships Macon and Akron were then designed and built to carry up to five F9C-2 scout planes that could be launched and recovered using a trapeze-shaped hook system (see Fig.1) (Smith, 1965). The program was cancelled after both of the airships crashed in bad weather, but this idea remained. The US Air Force has made several attempts later on. During World War II, the XF-85 Goblin was deployed from the bomb bay of the B-36 bomber as a parasite fighter. Two prototypes were constructed before the program was terminated. In late 1970s, the Boeing's 747 airliner was considered to be adapted in to a small fighter hangar and mothership (Atherton, 2014).

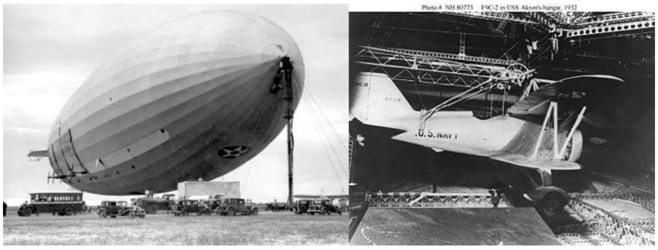

Figure 1. The US Naval ZRS-4 and the F9C-2 scout plane (Smith, 1965).

Along with the development of communication technology, Aerial Carriers seems become less and less important than before. However, it is considered valuable again for RPAS. Furthermore, in the near future, space carrier might become the essential traffic type in space and planet development.

1.3 *Brief introduction to current study condition*

The RPAS aerial carriers will launch and recover RPAS, and even the carriers themselves might be unmanned and remotely controlled. This means the new but dominant problem for RPAS aerial carrier today is the Autonomous Aerial Docking (AAD).

Currently, there exist no direct research achievements on this topic. There are only some hobbyist who have built an Avenger-like quadcopter that have a runway on it. A smaller fixed wing radio-controlled aircraft could take off from it. But the recovery was not considered.

Although no people work on AAD, there are many people work on similar topics: Autonomous Space Docking, Autonomous Underwater Vehicle (AUV) Docking, Autonomous Landing on a moving target, Autonomous Aerial Refuelling and the Robotic Autonomous Grasping. The docking technologies used by related papers are reviewed.

A general autonomous docking process has the following stages: target recognition & position estimation, position adjustment, and the mechanical guiding & locking. In these stages, the way of the position estimation is naturally determined by the method of the target recognition. So, the first two stages are treated as one, and they are the core part reviewed by this paper. Controller design is another big topic. A large number of people have worked on this. The guiding and locking structure is all about mechanical design, which makes the docking procedure easier and more reliable. Due to the article length, the review of these two parts are not included in this paper.

2 TARGET RECOGNITION & POSITION ESTIMATION TECHNOLOGIES

Target recognition and position estimation is the most important phase in the autonomous docking process. In this phase, the carrier recognizes the RPAS, and estimate their relative position. The result of the estimated position should be in the order of centimetres or lower (Mammarella *et al.*, 2010). The more accurate the estimation result is, the better performance the controller has. It also means more sufficient reaction in the proximity effect, and a more compact docking structure. However at the same time, for a more stable and faster responding control, this stage should not occupy too much computational resources, the corresponding measurement and processing delays must be kept to the minimum. In the application of autonomous landing, refuelling and grasping, due to the different conditions, different technologies were used.

2.1 *GPS*

GPS has become the most common method used today for positioning. However, the accuracy supplied by the free civilian GPS service (about 10 metres) is too coarse for aerial docking of small RPAS. By using differential GPS (DGPS) (Kaplan&Hegarty, 2005), the sub-metre level accuracy could be achieved. For military use and for some expensive commercial services the accuracy could be better. However, DGPS systems only cover local areas and not open to the public. Moreover, the frequency of such systems (around 300 kHz) is too low for real time tracking and positioning.

Generally, GPS systems still have the following issues: the requirement of clear sky, satellite drop out, hostile jamming and spoofing, and multipath effects. Because of these reasons, GPS is perfect for mission planning when the docking aircraft are far from each other. While at small distance, they will generally switch to another method for the position estimation (Fravolini *et al.*, 2004; Williamson *et al.*, 2009).

2.2 *Range detection*

Range finders provide point to point distance. It is generally used in 2D applications, e.g. ground mobile robots (Shoval&Borenstein, 2001). In 2D, the docking problem becomes superposing two segment lines in a plane. This problem could be calculated by triangulation (see Fig.2). In certain conditions, a 3D environment could be simplified in to 2D. For example, a quadcopter could hover at a certain altitude with the help of a high precision barometer. To use range sensors for position estimation saves a lot of computing power compared to image-based techniques.

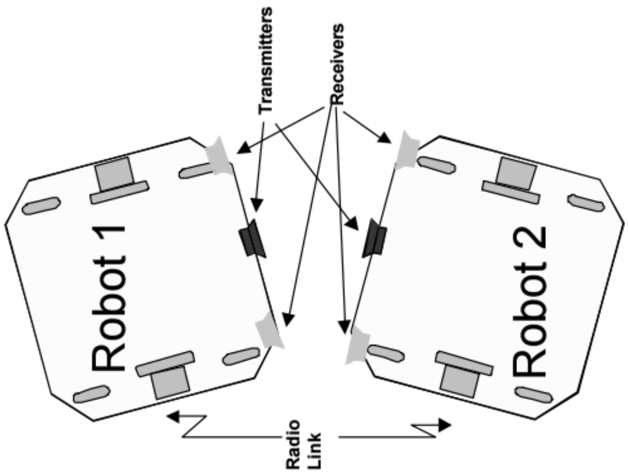

Figure 2. The basic sensor arrangement for measuring the relative position and orientation of two mobile robots using binaural ultrasonic sensors (Shoval&Borenstein, 2001).

2.3 *Gradient detection*

In AUV docking problems, a popular solution is to detect the strength gradient of light distribution (Sutantyo *et al.*, 2013). Chasing the brightest point is like walking down in a funnel, this method turns the 3D docking into a 1D movement. However it is based on an assumption that the two AUVs can keep in an identical docking plane. The accuracy of the sensors is not high (around 20 cm), but aided by some special mechanical structure, such as magnets coupling alignment (Sutantyo *et al.*, 2013) and conical cavity(Dunbabin *et al.*, 2009), it could be fixed. The gradient detection technologies are computationally cheap, but they are only suitable for underwater dark environment. If use microwave in the air, the accuracy is worse due to the lower frequency.

2.4 *3D mapping and modelling*

The 3D modelling is generally used by robots gasping jobs. The basic idea is to achieve the 3D point cloud of an unknown object, and then extract shape and position information from the model. For the application of aerial docking though, the small RPAS generally does not have sufficient computing power to do the modelling. Moreover, it is not necessary to rebuild the model of the target since the shape of it is already known.

The 3D point clouds are generally collected by the following methods: Structured Light, Scanning Laser Emitter, Stereo Camera, sonar, Kinect and Structure from Motion (SfM) with monocular camera. They are suitable for different conditions. After the point clouds are collected, the data needs to be processed. Most people create 3D features and descriptors such as spin images (Johnson, 1997). However, to rebuild the full model is too much computationally consuming. So many researches focused on optimizing the processing speed and reducing the computing power. Some typical algorithms are: taking use of partial shape information to reduce the amount of data (Eppner&Brock, 2013), or instead of rebuilding models, try to match the detected point clouds with samples in the database (Shin *et al.*, 2013). The latter algorithms always need extra training phases.

2.5 *2D Vision*

Computer Vision is a well-developed technology currently used on many applications, such as navigation, tracking, and recognition. Computer vision can not only provide very accurate position estimation in close distance, but also track a fast-moving target from long distance. However, the utilization of computer vision also suffers from the large computation resources required. Moreover, the reliability of vision systems are susceptible to environmental conditions such as cloud, fog, and lighting.

2.5.1 *Optical System on the target*

There are basically two types of target, positive and passive. As told by their name, positive target contains additional controllable light sources, such as identifiable beacons, LEDs (see Fig.3a) or lamps. By comparing images of the same scene with the sources switched on and off simplifies the extraction of the target and reduced the processing time (Wenzel *et al.*, 2011). The positive system can work in totally dark environment and bad weathers. But they usually require communication between the subject and the object, and they can also consume extra power.

On the contrary, a passive target doesn't have additional powered equipment. Instead, the detected and recognized features are usually some special signs (see Fig.3b), designed fiducial marks (see Fig.3c), partial features like the drogue for aerial refuelling (Yin *et al.*, 2014) or outlines of the target (see Fig.3d).

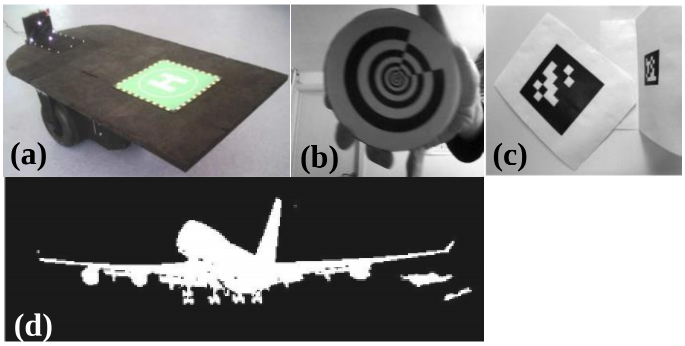

Figure 3. (a) LED arrays indicates the autonomous landing site. (b) Concentric circular mark for autonomous landing site (Wei *et al.*, 2013). (c) AprilTag for Augmented Reality, this tag can return 6DOF position and attitude information (Olson, 2011). (c) The shape of the tanker aircraft is extracted from the backgrond in an autonomous refuellig task (Khansari-Zadeh&Saghafi, 2011).

2.5.2 *Computer Vision Algorithms*

In particular, the procedure of vision position estimation is generally as follows:

First, use Thresholding (see Figure 3.c), Blurring or Morphology Processing to turn the captured image to binary image and reduce noise (Kaehler&Bradski, 2014). This step is very important for the reliability and validity of further processing. The algorithms need to be adaptive in changing environment and target brightness.

Next, key features are extracted from the image. Depends on targets, these include: edges, corners and blobs. Due to different algorithms, corner point coordination, blob area and blob centre, etc. could be extracted directly. For edges, Hough transform needs to be applied to convert irregular curves into regular shapes, e.g. lines, circles or eclipse (Zhu *et al.*, 2014).

After evaluation, the valid target is confirmed. There are two main approaches to calculate its position and orientation. For those outline-tracking scenarios, some kind of database point matching algorithms are preferred. For others, the perspective detection are normally used, in which there exist certain relations between the measured size and the target's state, given the camera is calibrated.

3 PROBLEMS IN AERIAL CARRIER DOCKING & FOR FUTURE STUDY

All the technologies and algorithms mentioned above are not developed for AAD. When adapting them into the AAD scenario, they will bring new problems.

Due to the size and payload limitation of small RPAS, high performance computer is not applicable. Hence, powerful but computationally expensive algorithms have to be abandoned in real-time processing. Whereas stationary hovering is a highly dynamic behaviour, especially in RPAS close proximity. Thus, the controller should be robust and reliable enough to keep the RPAS balance in any situation. This proposes a requirement of robust and efficient controller. It is hard for controller design, but according to the reviews, it is possible to simplify the problems by utilizing suitable detection sensors, position estimation strategies, control algorithms and mechanical docking structure designs.

In practice, the method of docking is related to many other questions. Such as:

- Aircraft types: balloon, multi-copter or fixed-wing?
- Communication strategies: analogue radio, digital data link (XBee), Wi-Fi, Bluetooth, or optical communication?
- Swarm algorithms: centralized or decentralized?
- Relations between the fuel capacity, the size of the RPAS and the mission coverage area.

4 CONCLUSION

Due to the development of the small civilian RPAS, the need of Aerial Carrier was proposed and caused people's interest. However, currently, there are seldom achievements on this area. The history of aerial carriers is reviewed, it is found that the essential difference today is the autonomous aerial docking, and the core part of AAD is position estimation. Thus, a review on position estimation technologies is presented, covering several related or similar topics. As a conclusion, many technologies could be utilised on the position estimation task, but for the small RPAS AAD scenario, they are facing the challenge of keeping balance between robustness and efficiency e.g. range or gradient detection is fast, but the accuracy is not high enough; 2D and 3D vision has the best robustness, but they are too computationally consuming. Actually this is a mutual problem of all the topics. However, in these topics, the problem can always be simplified by selecting proper strategies. So, all the aspects of the AAD scenario need to be carefully analysed and find out the most suitable solutions.

ACKNOWLEDGEMENT

The author is sponsored by the China Studentship Council.

REFERENCES

Atherton, K.D. 2014 *DARPA WANTS AIRBORNE AIRCRAFT CARRIERS*. Available from: http://www.popsci.com/article/technology/darpa-wants-airborne-aircraft-carriers [Accessed 11/11/2014].

Dunbabin, M., Corke, P., Vasilescu, I. and Rus, D. 2009 Experiments with cooperative control of underwater robots. *The International Journal of Robotics Research,* 28 (6), 815-833.

Eppner, C. and Brock, O. 2013 Grasping Unknown Objects by Exploiting Shape Adaptability and Environmental Constraints. *2013 Ieee/Rsj International Conference on Intelligent Robots and Systems (Iros)*, 4000-4006.

Fravolini, M.L., Ficola, A., Campa, G., Napolitano, M.R. and Seanor, B. 2004 Modeling and control issues for autonomous aerial refueling for UAVs using a probe–drogue refueling system. *Aerospace science and technology,* 8 (7), 611-618.

Johnson, A.E. 1997 *Spin-images: a representation for 3-D surface matching*, Citeseer.

Kaehler, A. and Bradski, G. 2014 *Learning OpenCV: Computer Vision with the OpenCV Library*, 2 ed.: O'Reilly Media.

Kaplan, E. and Hegarty, C. 2005 *Understanding GPS: principles and applications*. Artech house.

Khansari-Zadeh, S.M. and Saghafi, F. 2011 Vision-Based Navigation in Autonomous Close Proximity Operations using Neural Networks. *Ieee Transactions on Aerospace and Electronic Systems,* 47 (2), 864-883.

Mammarella, M., Campa, G., Napolitano, M.R. and Fravolini, M.L. 2010 Comparison of point matching algorithms for the UAV aerial refueling problem. *Machine Vision and Applications,* 21 (3), 241-251.

Olson, E. 2011 AprilTag: A robust and flexible visual fiducial system *Robotics and Automation (ICRA), 2011 IEEE International Conference on*. IEEE, 3400-3407.

Shin, Y.-D., Jang, G.-R., Park, J.-H., Bae, J.-H. and Baeg, M.-H. 2013 Integration of recognition and planning for robot hand grasping. *2013 10th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, 171-174.

Shoval, S. and Borenstein, J. 2001 Measuring the relative position and orientation between two mobile robots with binaural sonar *ANS 9th international topical meeting on robotics and remote systems, Seattle, Washington*.

Smith, R.K. 1965 The airships Akron & Macon: flying aircraft carriers of the United States Navy. US Naval Institute.

Sutantyo, D., Buntoro, D., Levi, P., Mintchev, S. and Stefanini, C. 2013 *Optical-guided Autonomous Docking Method for Underwater Reconfigurable Robot*.

Wei, X., Yin, Q., Peng, Y., Nie, H. and Liu, C. 2013 An overview of researches on deck-landing of carrier-based aircrafts. *2013 International Powered Lift Conference*, 12 pp.-12 pp.

Wenzel, K.E., Masselli, A. and Zell, A. 2011 Automatic take off, tracking and landing of a miniature UAV on a moving carrier vehicle. *Journal of intelligent & robotic systems,* 61 (1-4), 221-238.

Williamson, W.R., Glenn, G.J., Dang, V.T., Speyer, J.L., Stecko, S.M. and Takacs, J.M. 2009 Sensor fusion applied to autonomous aerial refueling. *Journal of Guidance, Control, and Dynamics,* 32 (1), 262-275.

Yin, Y., Xu, D., Wang, X. and Bai, M. 2014 Detection and Tracking Strategies for Autonomous Aerial Refuelling Tasks Based on Monocular Vision. *International Journal of Advanced Robotic Systems,* 11.

Zhu, Y., Jin, H., Zhang, X., Yin, J., Liu, P. and Zhao, J. 2014 A Multi-sensory Autonomous Docking Approach for a Self-reconfigurable Robot without Mechanical Guidance. *International Journal of Advanced Robotic Systems,* 11.