

PARTICLE FILTER LOCALIZATION FOR UNMANNED AERIAL VEHICLES USING AUGMENTED REALITY TAGS

EDWARD FRANCIS KELLEY V

PRINCETON UNIVERSITY
DEPARTMENT OF COMPUTER SCIENCE

ADVISORS:
PROFESSOR SZYMON RUSINKIEWICZ
PROFESSOR ROBERT STENGEL

MAY 2013

Abstract

This is my abstract.

Acknowledgements

I want to thank me.

To my parents.

Contents

Abstract	ii
Acknowledgements	iii
List of Figures	viii
1 Introduction	1
1.1 Motivation	2
1.2 Current Acquisition Methods	2
1.2.1 Manual Model Creation	2
1.2.2 Laser Scanners	2
1.2.3 Multi-View Stereo	3
1.2.4 Stereo Vision with Infrared Pattern	4
1.3 Problem Definition	4
1.4 Proposed Solution	5
2 Related Work	6
2.1 Quadcopters for Model Acquisition	6
2.2 GPS-denied Navigation of Quadcopters	7
2.3 Research projects using the AR.Drone	7
3 System Design	8
3.1 Quadcopter Characteristics	9
3.1.1 Basics of Quadcopter Flight	9

3.1.2	Benefits	9
3.1.3	Limitations	9
3.2	Parrot AR.Drone 2.0	9
3.2.1	Features	10
3.2.2	Limitations	11
3.3	System Architecture	12
3.3.1	Robot Operating System	12
3.3.2	ardrone_autonomy	13
3.3.3	ARToolKit	13
3.3.4	Localization	14
3.3.5	Controller	14
3.3.6	Agisoft Photoscan	14
4	Localization	15
4.1	Problem Description	15
4.2	Considerations of the AR.Drone	16
4.3	Potential Solutions	16
4.4	Particle Filter	16
4.4.1	Buffering Navdata	16
4.4.2	Propagation Step	16
4.4.3	Correction Step	17
5	Results and Analysis	18
5.1	Sensor Testing	18
5.1.1	Gyroscope	18
5.2	Localization	18
5.3	Controller	18
5.4	Model Generation	18

6 Conclusion	19
A Implementation	20
Bibliography	21

List of Figures

1.1	An example of a laser scanner setup used by the Digital Michelangelo Project [19].	3
1.2	A 3D model of a statue generated by Agisoft Photoscan. Notice the derived camera planes encompassing the statue [1].	4
3.1	Parrot AR.Drone 2.0[8]	8
3.2	Augmented Reality Tag With ID 42	14

Chapter 1

Introduction

In recent years, research using micro aerial vehicles (MAVs) has increased rapidly. Multi rotor aircraft, such as quadcopters (also known as quadrotors), have proven to be powerful platforms for applications in a variety of fields, from aerial photography to search and rescue.[] Once prohibitively expensive, multi rotor aircraft have decreased substantially in price, ranging from a few hundred dollars to several thousand dollars. Additionally, on-board control systems have greatly added to the stability and ease of control of these aircraft, with many quadcopters using pre-programmed routines for difficult procedures such as takeoff and landing.

Although quadcopters have seen interest from the military and hobbyists for quite some time, these recent developments in price and stability have resulted in these aircraft being used in a wide array of applications. In 2010, a French company, Parrot, released the AR.Drone, a quadcopter intended for consumers. Unlike most other quadcopters, which were sold in kits targeted to experienced hobbyists or researchers, the AR.Drone was designed to be ready to fly right out of the box by an inexperienced pilot. Although affordable and easy to use, these quadcopters are far from just toys. Equipped with an array sensors and multiple cameras, the AR.Drone and other

consumer-grade vehicles have been used by research groups to explore autonomous flight with a low barrier of entry, both in cost and complexity.

With the democratization of this technology, quadcopters can be used to be solved problems where cost and complexity for such a solution was once prohibitive. This thesis explores the development of the localization component for an autonomous 3D model capture system using consumer-grade quadcopters.

1.1 Motivation

For applications ranging from developing video games to preserving archaeological artifacts, capturing 3D models of real-world objects has become an important task in a wide variety of fields.

While there are currently several different methods for capturing these models, each of these methods have associated limitations and drawbacks.

1.2 Current Acquisition Methods

1.2.1 Manual Model Creation

1.2.2 Laser Scanners

Laser rangefinder technology is the “gold standard” of 3D model acquisition in terms of precision. Modern scanners can produce sub millimeter scans, which make them a great choice for detailed digitization of statues. Combined with high-resolution photograph texture-mapping, very few techniques can match the precision and quality of these scans. The Digital Michelangelo Project showed the power and precision of laser scanners by scanning several different statues, including Michelangelo’s David, to 1/4mm accuracy.[19]



Figure 1.1: An example of a laser scanner setup used by the Digital Michelangelo Project [19].

However, laser scanners do have several drawbacks. The equipment is extremely expensive, bulky, and fragile. The Michelangelo Project had to transport over 4 tons of equipment to Italy in order to produce their scans. Additionally, laser scans involve immense setup and can take many hours. The scan of David took over a thousand man-hours to scan and even more than that in post processing [19].

1.2.3 Multi-View Stereo

Multi-view stereo uses a collection of 2D images to reconstruct a 3D object model. By viewing a single object from hundreds of different camera positions, a 3D model can be generated. Although this technique originally required precisely known camera coordinates, recent algorithms can produce a 3D model from an unordered collection of images with unknown camera positions, assuming that there is sufficient coverage. Existing software packages such as Bundler and Agisoft Photoscan can produce high-quality 3D reconstructions using these unordered image collections. [6][1]

The ability to use a collection of images without precise camera position information means that these 3D objects can be modeled substantially faster than with

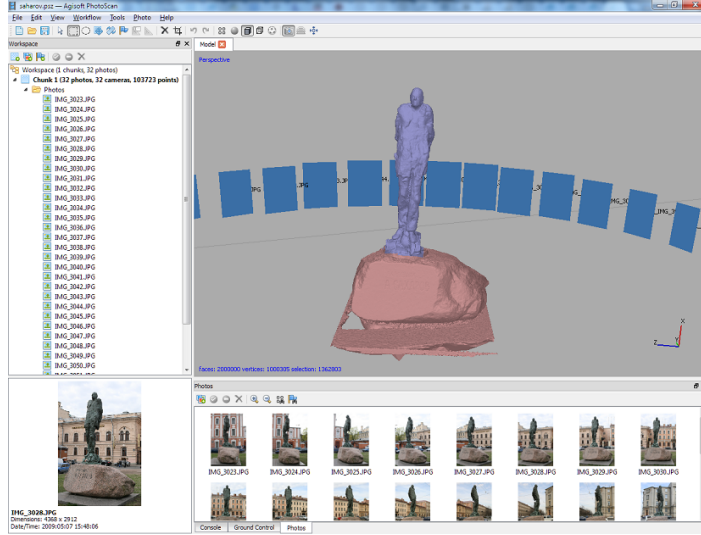


Figure 1.2: A 3D model of a statue generated by Agisoft Photoscan. Notice the derived camera planes encompassing the statue [1].

a laser scanner. With a smaller object, it is a relatively simple process to take pictures of the object from many different angles. However, for a larger object, such as a statue or building, the problem of gathering imagery becomes substantially more difficult.

1.2.4 Stereo Vision with Infrared Pattern

1.3 Problem Definition

We look to create a system to capture imagery of large 3D objects for use in multi-view stereo software. This system has several requirements.

1. Low Cost

The system should be substantially cheaper than laser scanning.

2. Easy to Use

This system should be able to be deployed by users with minimal training.

Additionally, the hardware should be off-the-shelf and easily accessible.

3. Complete Coverage

The system must be able to capture images from a wide variety of positions, completely covering every part of the target object.

4. High Quality Imagery

The system must produce sufficiently high resolution, non-blurry images for use in multi-view stereo software.

1.4 Proposed Solution

We propose using low-cost autonomous quadcopters to gather imagery needed for use in multi-view stereo software. By flying a quadcopter with a mounted camera around the target object, we can quickly and thoroughly capture images of the target from a wide variety of positions. Using quadcopters has many advantages.

1. Quadcopters can capture images from positions unreachable by ground-based cameras.
2. By methodically flying around the target object at different altitudes, we can guarantee complete coverage of the target object.
3. The imagery can be captured very quickly, on the order of a few minutes.
4. Quadcopters are small, portable, and easily deployable.

Chapter 2

Related Work

2.1 Quadcopters for Model Acquisition

The past decade has seen a huge increase in the use of quadcopters for a variety of applications. With the improvement of stabilization software, quadcopters have seen a rise in popularity as a stable, cheap, and highly maneuverable aerial platform.

Although a relatively new field, several research groups have studied the use of quadcopters in 3D model construction. Irschara et al. created a system to generate 3D models using images taken from UAVs. While a quadcopter was used for gathering imagery, the quadcopter was manually controlled and the main focus of their work was photogrammetry-based model creation [15]. Steffen et al. studied surface reconstruction using aerial photography captured by UAVs [24].

Most relevant to our work, Engel et al. published multiple papers on the camera-based navigation and localization of the AR.Drone. While they were able to achieve very accurate navigation, their work relies on the drone facing a mostly planar surface during the entire flight, a constraint that is not possible in our application.

2.2 GPS-denied Navigation of Quadcopters

2.3 Research projects using the AR.Drone



(a) Indoor Hull



(b) Outdoor Hull

Figure 3.1: Parrot AR.Drone 2.0[8]

Chapter 3

System Design

3.1 Quadcopter Characteristics

3.1.1 Basics of Quadcopter Flight

3.1.2 Benefits

3.1.3 Limitations

3.2 Parrot AR.Drone 2.0

This system will use the AR.Drone 2.0, the second generation of the consumer-grade quadcopter released by Parrot in 2010. The AR.Drone is a stabilized aerial platform that can be controlled by a user-friendly interface on a variety of mobile devices such as the Apple iPhone or iPad. The quadcopter is equipped with cameras and can be used for recording videos and playing augmented reality games.

Forward Camera	HD, 720p 92° diagonal viewing area
Bottom Camera	QVGA, 320x240 64° diagonal viewing area
Computational Resources	1 GHz ARM Cortex-A8 CPU 800 MHz Video Digital Signal Processor 256 MB (1 Gbit) DDR2 RAM
Networking	802.11n WiFi
Sensors	3-axis gyroscope (2000 degree/second) 3-axis accelerometer (+/- 50 mg precision) 3-axis magnetometer (6 degree precision) Pressure sensor (+/- 10 Pa precision) Ultrasound altitude sensor

Table 3.1: AR.Drone 2.0 Technical Specifications [10]

3.2.1 Features

Considering its target audience of consumers, the AR.Drone is actually a very powerful research platform. The quadcopter is ready-to-fly out of the box. Unlike most quadcopters which are sold as kits, there is no assembly or technology knowledge needed to get started. Additionally, with the provided SDK, it is relatively easy to get off the ground and start running code to control the quadcopter. Finally, at only \$300, the AR.Drone is much easier to fit into most research budgets than kit quadcopters which can cost thousands of dollars.

The AR.Drone has two cameras, one forward-facing HD camera, and one lower resolution high frame-rate camera facing downwards. The AR.Drone processes the visual imagery on board to produce a velocity estimate. Depending on the ground material and lighting quality, the AR.Drone uses either multi-resolution optical flow or FAST corner detection with least-squares minimization. The drone also uses the

gyroscope and accelerometer on the navigation board to produce a velocity estimate and fuses this estimate with the vision-based velocity to create a relatively robust velocity estimation.[10]

For altitude estimation, the AR.Drone uses a combination of an ultrasonic range sensor and pressure sensor. At heights under 6 meters, the AR.Drone relies solely on the ultrasonic sensor. Above those heights, where the ultrasonic sensor is not in its operational range, the AR.Drone estimates altitude based on the difference between the current pressure and the pressure measured on takeoff.

The on-board processor handles low-level stabilization and wind compensation, allowing the quadcopter to hold position when not receiving control inputs. Commands to the AR.Drone are sent in the form of desired pitch and roll angles for translational movements, angular rate for yaw adjustment, and velocity for altitude adjustments. These high level commands are then translated by the on-board controller into rotor speed adjustments. Typically difficult actions, such as takeoff and landing, are completely handled by the onboard control. When the takeoff command is issued, the AR.Drone quickly takes off to a default height and hovers before accepting any movement commands.

3.2.2 Limitations

While the AR.Drone is a great platform for many research projects, it does have limitations when compared to hobbyist or professional-grade quadcopters.

The hardware design allows for very little customization. While most professional-grade quadcopters have ports for adding additional sensors, there is no straightforward way to add any electronics to the AR.Drone. Even if it were possible to customize, the AR.Drone is designed to only lift its own weight, with most hobbyists claiming to get a maximum of 100 grams payload before the flight characteristics are significantly

affected.[2] Professional quadcopters of a similar size are typically able to fly with payloads between 400 and 600 grams.[7]

Another limitation of the AR.Drone is the flight time. The maximum flight time of the AR.Drone is only around 15 minutes, with the additional weight of the indoor hull bringing this down to 10-12 minutes. Similar sized quadcopters, such as the Mikrocopter, typically achieve around 30 minutes of flight time, depending on weight and battery size.[7]

Additionally, the AR.Drone has no built in GPS system, meaning that the on board measurements provide only relative measurements. This leads to errors in drift and makes flying autonomously in a precise pattern an extremely challenging task.

Finally, as the AR.Drone was designed to be used by inexperienced pilots, extra emphasis was put on making the quadcopter durable when it is inevitably crashed. Due to this, the polystyrene case and hull, particularly the indoor hull, around the body are much larger than that of the Mikrocopter or similar quadcopters. This results in a larger surface area that can be affected by the wind, making outdoor flights particularly difficult even with the on board stabilization.

3.3 System Architecture

3.3.1 Robot Operating System

This system will use the Robot Operating System (ROS) to organize the interaction between programs and libraries. Although not an “operating system” in the traditional sense, ROS is an open source communication layer used in a wide variety of robotics applications. Supported by Willow Garage, ROS has a large amount of documentation and packages which can handle a large number of common tasks in robotics. Many of these packages are hardware-independent, meaning that they can be quickly implemented on an array of different robotics system. ROS also provides a

standard message protocol, allowing packages to work together in a language agnostic manner.[22][9]

3.3.2 ardrone_autonomy

“ardrone_autonomy” is an open-source ROS wrapper for the Parrot AR.Drone SDK developed in the Autonomy Lab at Simon Fraser University.[3] This package handles the interface of navdata messages, video feeds, and control commands between ROS and the AR.Drone. This allows the use of many existing ROS packages in localizing and controlling the quadcopter.

3.3.3 ARToolKit

ARToolKit is an open-source software library designed to be used for creating Augmented Reality applications. Developed by Dr. Hirokazu Kato and maintained by the HIT lab at the University of Washington, ARToolKit uses computer vision algorithms to identify fiduciary markers, such as the one in Figure 3.2, and calculate the transformation between camera and tag orientation.

For augmented reality applications, this can be used to superimpose 3D graphics onto a video feed in real time based on the tag position and orientation. In this system, the tags will be used to generate global positioning estimates for the quadcopter by combining estimated tag transformations with known tag locations.

Specifically, ARToolKit will be implemented using a slightly modified version of the “ar_pose” library, a ROS wrapper for ARToolKit developed by Ivan Dryanovski et al. at the CCNY robotics lab.[4]

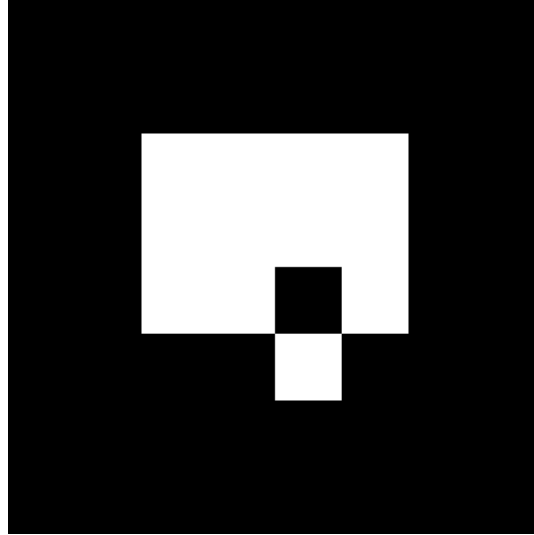


Figure 3.2: Augmented Reality Tag With ID 42

3.3.4 Localization

3.3.5 Controller

3.3.6 Agisoft Photoscan

Chapter 4

Localization

4.1 Problem Description

For a robot to perform precise maneuvers, it must first have an understanding of its position and orientation. This is the problem of localization. By using a variety of sensor measurements, each with sources of error, the localization algorithm must produce a single estimate of the quadcopter's pose for use in the controller.

Algorithm 1 Particle Filter with Augmented Reality Tag Correction

```
1: for all  $t$  do
2:   if  $buffer\_full()$  then
3:      $propagate(t_\delta, v_x, v_y, altd, \theta)$ 
4:   end if
5:   if  $recieved\_tag()$  then
6:      $ar\_correct(\mathbf{M})$   $\triangleright$  Transformation matrix from camera to marker
7:   end if
8:    $x_{est} \leftarrow get\_estimate()$ 
9: end for
```

Algorithm 2 Particle Filter Propogation

```
1: function PROPOGATE( $t_\delta, v_x, v_y, altd, \theta$ )
2:   for  $i = 1 \dots N$  do
3:      $x_{current} \leftarrow x_{t-1}[i]$ 
4:      $x_t[i] \leftarrow n$ 
5:   end for
6: end function
```

4.2 Considerations of the AR.Drone

4.3 Potential Solutions

4.4 Particle Filter

4.4.1 Buffering Navdata

4.4.2 Propagation Step

Adding Noise to Sensor Measurements

Converting Local Velocity to Global Velocity

$$\begin{bmatrix} V_{x,global} \\ V_{y,global} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} V_{x,local} \\ V_{y,local} \end{bmatrix}$$

Algorithm 3 Particle Filter Augmented Reality Tag Correction

```
1: if  $i \geq maxval$  then  
2:    $i \leftarrow 0$   
3: else  
4:   if  $i + k \leq maxval$  then  
5:      $i \leftarrow i + k$   
6:   end if  
7: end if
```

4.4.3 Correction Step

Determining Global Position from Augmented Reality Tag

Weighting Particles

Weighted Sampling of Particles

Random Resampling

Chapter 5

Results and Analysis

5.1 Sensor Testing

5.1.1 Gyroscope

5.2 Localization

5.3 Controller

5.4 Model Generation

Chapter 6

Conclusion

Appendix A

Implementation

Bibliography

- [1] Agisoft photoscan. <http://www.agisoft.ru/products/photoscan>.
- [2] Ar.drone forum: Weight capacity. <http://forum.parrot.com/ardrone/en/viewtopic.php?id=4545>.
- [3] ardrone_autonomy. https://github.com/AutonomyLab/ardrone_autonomy.
- [4] ar_pose. http://www.ros.org/wiki/ar_pose.
- [5] Artoolkit. <http://www.hitl.washington.edu/artoolkit/>.
- [6] Bundler: Structure from motion (sfm) for unordered image collections. <http://phototour.cs.washington.edu/bundler/>.
- [7] Mk-quadrokopter. <http://www.mikrokopter.de/ucwiki/en/MK-Quadro>.
- [8] Parrot Press Photos. <http://ardrone2.parrot.com/photos/photo-album/>.
- [9] Brian Berard. *Quadrotor uav interface and localization design*. PhD thesis, WORCESTER POLYTECHNIC INSTITUTE, 2010.
- [10] Pierre-Jean Bristeau, Franois Callou, David Vissire, and Nicolas Petit. The navigation and control technology inside the ar.drone micro uav, 2011.
- [11] Nick Dijkshoorn. Simultaneous localization and mapping with the ar.drone, 2012.
- [12] J. Engel, J. Sturm, and D. Cremers. Accurate figure flying with a quadcopter using onboard visual and inertial sensing. *IMU*, 320:240.
- [13] J. Engel, J. Sturm, and D. Cremers. Camera-based navigation of a low-cost quadcopter. In *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, pages 2815 –2821, oct. 2012.
- [14] Dieter Fox, Sebastian Thrun, Wolfram Burgard, and Frank Dellaert. Particle filters for mobile robot localization, 2001.
- [15] A. Irschara, V. Kaufmann, M. Klopschitz, H. Bischof, and F. Leberl. Towards fully automatic photogrammetric reconstruction using digital images taken from uavs. In *Proceedings of the ISPRS TC VII Symposium 100 Years ISPRS*, 2010.

- [16] Hirokazu Kato. Artoolkit: library for vision-based augmented reality. *IEICE, PRMU*, pages 79–86, 2002.
- [17] Tomáš Krajník, Vojtěch Vonásek, Daniel Fišer, and Jan Faigl. Ar-drone as a platform for robotic research and education. In *Research and Education in Robotics-EUROBOT 2011*, pages 172–186. Springer, 2011.
- [18] K.Y.K. Leung, C.M. Clark, and J.P. Huissoon. Localization in urban environments by matching ground level video images with an aerial image. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 551–556, may 2008.
- [19] Marc Levoy, Kari Pulli, Brian Curless, Szymon Rusinkiewicz, David Koller, Lucas Pereira, Matt Ginzton, Sean Anderson, James Davis, Jeremy Ginsberg, Jonathan Shade, and Duane Fulk. The digital michelangelo project: 3d scanning of large statues. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, SIGGRAPH '00, pages 131–144, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co.
- [20] Joao Pedro Baptista Mendes. Assisted teleoperation of quadcopters using obstacle avoidance. 2012.
- [21] Rudy Negenborn. *Robot localization and kalman filters*. PhD thesis, Citeseer, 2003.
- [22] Morgan Quigley, Ken Conley, Brian Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Rob Wheeler, and Andrew Y Ng. Ros: an open-source robot operating system. In *ICRA workshop on open source software*, volume 3, 2009.
- [23] Szymon Rusinkiewicz, Olaf Hall-Holt, and Marc Levoy. Real-time 3d model acquisition, 2002.
- [24] R. Steffen and W. Förstner. On visual real time mapping for unmanned aerial vehicles. In *21st Congress of the International Society for Photogrammetry and Remote Sensing (ISPRS)*, pages 57–62, 2008.
- [25] Teddy Yap, Mingyang Li, Anastasios I. Mourikis, and Christian R. Shelton. A particle filter for monocular vision-aided odometry.