Relative Pose Estimation for an Integrated UGV-UAV Robot System

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Abstract. We have designed an integrated system of an UGV (Unmanned Ground Vehicle) and an UAV(Unmanned Aerial Vehicle), and propose a sensor-based relative pose estimation method for this system. Most of service robots are wheeled robots which can be easily controlled. However, due to the development of aerial vehicle technologies including sensors and wireless communication, recent UAVs can have lower weight, longer flight time and stabilized control system. Merging an UGV and an UAV for certain service can be a better choice for personal or public services, especially for effective surveillance. In this paper, a commercial μUAV and a low-price, sensor-equipped mobile base are integrated to provide surveillance service. A fish-eye camera and an ultrasonic range finder sensor are utilized to estimate relative translation between two robots. Attitude and heading reference systems in both robots are utilized to estimate relative rotation between them. The probabilistic filter is applied to compensate sensor or camera measurement noises. The robustness of the proposed system is verified by a quad-camera stereo capture system. Also, practical application is provided with a scenario which performs the homing of the UAV from arbitrary location.

Keywords: UGV, UAV, relative pose, co-operation.

1 Introduction

1.1 Integration of UGV and UAV

The public demand for service robots is steadily increasing. According to *International Federation of Robotics(IFR)*, the number of service robots sold for personal and household was estimated more than 2.5 million in 2011, which was 15% more than that of 2010[1]. Most of the service robots move with attached wheels, which are stable and very easy to control.

However, wheels severely limit the movable range of service robots. For example, most of commercial bi-wheeled robotic vacuum cleaner cannot pass through

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even a very low door sill. On outdoor application, automobiles cannot pass through a wall without making a hole. To overcome such obstacles, additional paths such as slopes or another moving means are required.

One of the candidate is wing. But due to difficulties, complexity and limits of the aerial vehicle control, they are not suitable to provide personal or household services. However, aerial vehicle technologies have been much developed these days. The weight of aerial vehicles have been decreased thanks to the advanced materials, and flight time has become longer with battery technologies. MEMS-based sensor equipments allow the stable control of aerial vehicles, and wireless communication technologies enable remote controllability and connectivity exchanging camera or sensory information between the robot and the station. These days, aerial vehicles are no longer a special technology. They are utilized not only for public transportation or military service, but also for hobbies and toys.

The wheeled robots are easy to control and comparatively free from the payload and energy limit, while aerial robots have much wider field of operations. Therefore, integrating two robots to provide surveillance services can take advantage of both of them. The ground one can patrol the desired region, and can deploy the aerial one to investigate unreachable regions. In this paper, a commercial μUAV and a low-price, sensor-equipped mobile base are integrated to provide surveillance services.

1.2 Related Works

Recently, the aerial vehicle has become one of popular research fields of robotics. Researches for rapid and complex motion control of them[2], or their cooperation for manipulation or transportation[3] have been performed. Autonomous flight is also a popular issue. Autonomous flight with structed[4] or unstructed[5] environment was presented.

As mentioned in 1.1, the aerial vehicles are not free from the payload. This constraint limits the quantity of sensors or processors to be attached on the vehicle. Overcoming this limit and to achieve successful localization, the GPS-based method for outdoor environments[6] and artificial landmark-based method for indoors[7] are introduced. To compensate weak computational power, sensor data can be transferred to ground station[8].

To provide indoor service with the aerial vehicle, the aerial vehicle requires various sensors in small size. A commercial quadcopter, AR.Drone 2.0[9] is equipped with 2 cameras, a 9-axis inertial measurement unit(IMU), an ultrasonic altitude sensor with wireless communication ability. A periodical surveillance system have been introduced[10] utilizing this μUAV and a mobile base. To localize the aerial vehicle, the bottom camera was utilized to observe the mobile base and the dead-reckoning method with internal IMU was applied. Because of the dead-reckoning method, the ground vehicle must stand still while the aerial vehicle is in flight.

1.3 Problem Definition

To perform services with multiple robots in cooperation, localizing both of them is one of the most important issues. Without an accurate localization, they might be crash into each other during the task, or their task paths could be overlapped unnecessarily. Relative localization is also an essential issue. With an absolute position of a robot and the relative position with another robot, the absolute position of the other can be determined.

In this paper, a commercial μUAV and a low-price, sensor-equipped mobile base are integrated to provide surveillance services. To estimate the relative pose between them, a fish-eye camera, an ultrasonic range finder sensor, two IMUs are utilized.

The probabilistic filter is applied to compensate sensor/camera measurement noises. The robustness of the proposed system is verified by a quad-camera stereo capture system. Also, a practical application is provided with a scenario which performs the homing of the UAV from an arbitrary location.

2 Relative Pose Estimation Using Sensor Fusion

Pose estimation of certain object requires 2 elements; the rotation and the translation. To estimate relative pose of 2 objects, it is necessary to set a reference coordinate system. In this work, the camera center of the ground vehicle is the origin of overall coordinate system. The relative rotation and the translation can be easily calculated by estimating the position of aerial vehicle, (x_a, y_a, z_a) and the rotation of aerial vehicle, d_a in Fig. 2.

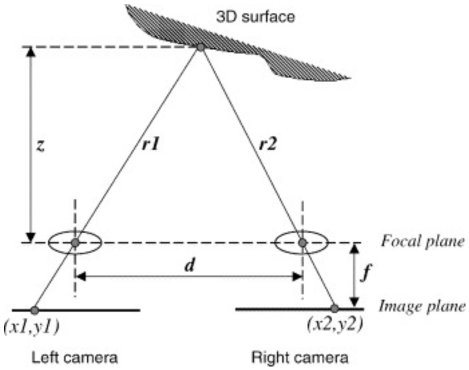

Fig. 1. Estimation of 3D position using 2-camera stereo system. $x1$, $y1$, $x2$, $y2$: the position in the pixel plane. d: distance between cameras. f: focal length.

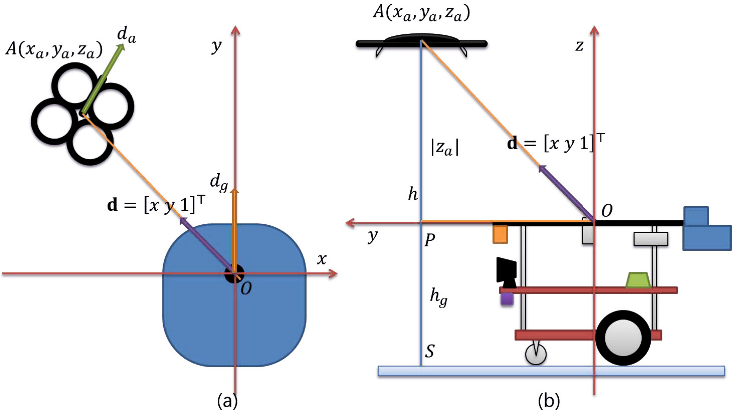

Fig. 2. The relative pose of two robots. (a) $x - y$ plane. (b) $y - z$ plane. h_g: predefined height of the ground vehicle, $\mathbf{d} = [x \quad y \quad 1]^\top$: direction vector of the aerial vehicle from the ground vehicle, h: height of the aerial vehicle, d_a: direction of the aerial vehicle, d_g: direction of the ground vehicle.

2.1 Relative Rotation Using Inertial Measurement Units

An inertial measurement unit has three 3-axis sensors to estimate its rotation matrix; a gyroscope, an accelerometer and a magnetometer. If it is attached to a robot, its estimated rotation matrix can be treated as the robot rotation matrix. The rotation of a vehicle can be described with three variables, *roll, pitch* and *yaw* as in Fig. 3. So, the difference of the values of two vehicles can be treated as their relative rotation.

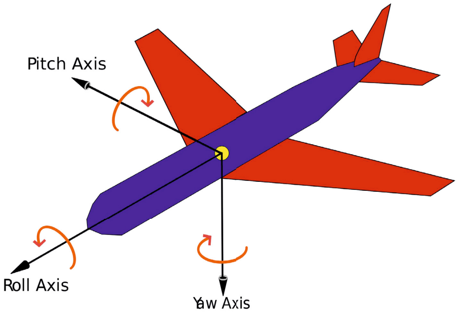

Fig. 3. Tait-Bryan notation of a vehicle

2.2 Relative Position Using Sensor Fusion

Among the methods to estimate three-dimensional position of an object[11], the most representative one is the 2-camera stereo. The 2-camera stereo system estimates the position of an object by triangulation, as in Fig. 1. To estimate the exact position, the distance between cameras d should be long enough. In the proposed system, upward camera system for observing the aerial vehicle is attached on top of the ground vehicle. So, it is not efficient to attach two or more cameras on the robot with ensuring large d, due to the limit of the size of ground vehicle.

Instead of the 2-camera stereo, we utilized a fish-eye camera and the altitude of the aerial robot. With the information of ray direction d and the altitude of the aerial vehicle h in Fig. 2, it is possible to estimate the relative position between two robots as (1) which is represented as $A(x_a, y_a, z_a)$.

$$\begin{aligned} x_a &= |z_a|x \\ y_a &= |z_a|y \\ z_a &= h - h_g \end{aligned} \tag{1}$$

2.3 Estimating Ray Direction From Fish-Eye Camera

If one can extract a target object from the image captured from a camera, it is possible to estimate the direction of the object from the camera center. Fig. 4 shows the geometric model of a pinhole camera. In this camera model, the real point X is projected to the point x on the image plane. From the properties of similar figures, the point x= (x, y, f) can be represented with X= (X, Y, Z) as $(fX/Z, fY/Z, f)$. It is possible to determine the ray direction of any projected points on the image plane after the camera calibration process[12].

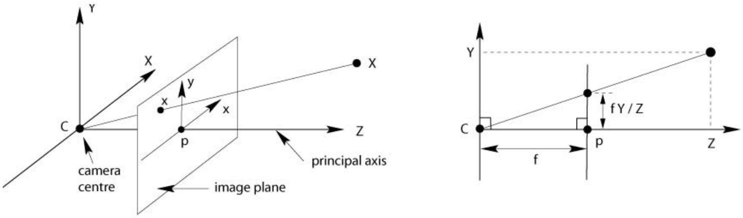

Fig. 4. Pinhole camera model

2.4 Estimating Altitude with Ultrasonc Sensor

The ultrasonic sensor range finder measures the distance between the sensor and a surface. If the sensor is attached to the bottom of an aerial vehicle and the vehicle is in flight, the sensor can estimate the altitude of the aerial vehicle. The response of the sensor is almost linear, but the response signal has uncertainties due to the ADC circuit noise or the temperature of the air.

3 Probabilistic Filter Compensating Measurement Error

Section 2 describes how to estimate the relative pose between two robots with the direction vector and the altitude of the aerial vehicle. But measurement errors can be occured because of various reasons. Dominant errors are the altitude measurement error with the ultrasonic range finder and the image measurement error during the extraction the aerial vehicle from the fish-eye camera captured image. The probabilistic filter determines the relative position with the estimated pose and the model of noise from the image measurement and the ultrasonic sensor response.

Estimated position of the aerial vehicle at time t can be denoted as $X_t = [x_t \quad y_t \quad z_t]^\top$. Also, observed position in t can be denoted as Z_t.

3.1 Probabilistic Model for Position Estimation

The objective of the probabilistic position estimation is updating X_t with respect to the variation of observation Z_t as (2) and Fig. 5.

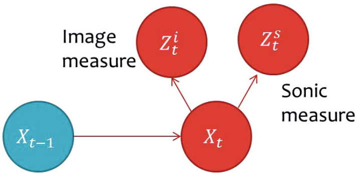

Fig. 5. Probabilistic Position Estimation

$$P(X_t|Z_{1:t}) = \eta P(Z_t|X_t)P(X_t|Z_{1:t-1}) \tag{2}$$

If the observed positions from $t = 0$ to $t-1$ are known, the predicted position can be modeled as (3).

$$P(X_t|Z_{1:t-1}) = \int_{X_{t-1}} P(X_t|X_{t-1})P(X_{t-1}|Z_{1:t-1})dX_{t-1} \tag{3}$$

$P(X_t|X_{t-1})$is called motion model and $P(Z_t|X_t)$ is called measurement model in (2) and (3).

3.2 Motion Model

Motion model describes the variations of relative position between two robots. To simplify the problem, conventional motion models assume the uniform velocity of robot or use sensors to observe exact velocity[13]. But in this research, two robots move separately. Also, the velocity of the aerial vehicle cannot be measured explicitly. So, it is impossible to assume uniform velocity or observe exact velocity. So, the motion model $P(X_t|X_{t-1})$ is modeled as Gaussian random variable.

3.3 Measurement Model

Measurement model with the position of the aerial vehicle in captured image pixel plane u_m and reprojection of X_t in image plane $\hat{u}$ can be formulated as (4).

$$\exp(-\frac{||u_m - \hat{u}||}{2\sigma_p^2}) \tag{4}$$

Similar model can be derived as (5) for the ultrasonic measurement model.

$$\exp(-\frac{||z - h||}{2\sigma_h^2}) \tag{5}$$

The response of the ultrasonic sensor and the extraction from captured image are independent, so the measurement model can be derived by multiplying them as (6).

$$P(Z_t|X_t) = P(Z_t^i|X_t)P(Z_t^s|X_t) = \exp(-\frac{||u_m - \hat{u}||}{2\sigma_p^2})\exp(-\frac{||z - h||}{2\sigma_h^2}) \tag{6}$$

4 Experiments

4.1 An Integrated System of an UGV and an UAV

Integrated robot system consists of two robots; an unmanned ground vehicle and an unmanned aerial vehicle. The bi-wheeled ground vehicle has a flat plate to carry the aerial vehicle. The aerial vehicle can take off or land on the station. A fish-eye camera is attached on the station.

The aerial vehicle is selected within the commercial small ones. AR.Drone 2.0[9] mentioned in 1.2 is a commercial quadcopter equipped with various sensors to be easily controlled. Also, with wireless communication technologies, users can not only control the robot but also retrieve sensory informations and camera images from the robot. To detect the aerial vehicle easily, we attached a LED array under the aerial vehicle. Fig. 6 shows the appearance of the integrated system.

4.2 Evaluation Setup

To evaluate the accuracy of the proposed method, we designed a quad-camera stereo capture system as Fig. 7. Four cameras are synchronized with the fish-eye camera and the ultrasonic altitude sensor of the UAV, to capture the path of the UAV. The captured path recorded by external four cameras is treated as the ground truth. The accuracy of proposed system is evaluated by calculating the error of Euclidean distance.

Fig. 6. Integrated Robots: Front view, Fisheye Camera, Landed aerial vehicle, Bottom view, Ultrasonic altitude sensor

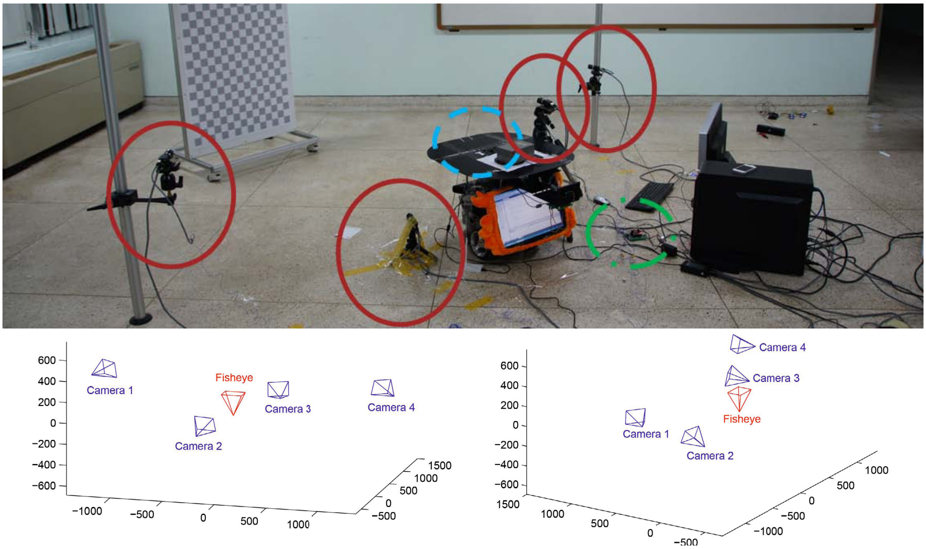

Fig. 7. Calibration of the quad-camera stereo capture system. Solid line: 4 cameras, Dashed line: fisheye camera attached to robot, Chain line: external synchronized trigger. Camera center of the fisheye camera is the origin of the world coordinates. 4 cameras are calibrated and firmly attached.

4.3 Experimental Result

Fig. 8 shows the result of estimation of relative position. The first one is the case of the smooth movement. In that case, the response of the ultrasonic sensor is comparatively stable. The second one is the case of the rapid movement, so the response of the ultrasonic sensor is distorted with noise. Table 1 is the error from the each experiment.

Table 1. Mean error of captured data

UAV Movement	Captured	Filtered
Smooth	106.38mm	103.51mm
Rapid	82.69mm	78.54mm

4.4 Autonomous Homing of the UAV

To show the possibility of practical application of the proposed method, we designed a scenario. To perform a surveillance service with this integrated system, each robot should perform its duty with different path. However, after the surveillance of the UAV, the aerial one must return to the base for safety and power issues. In this experiment, we perform the autonomous homing of the unmanned aerial vehicle.

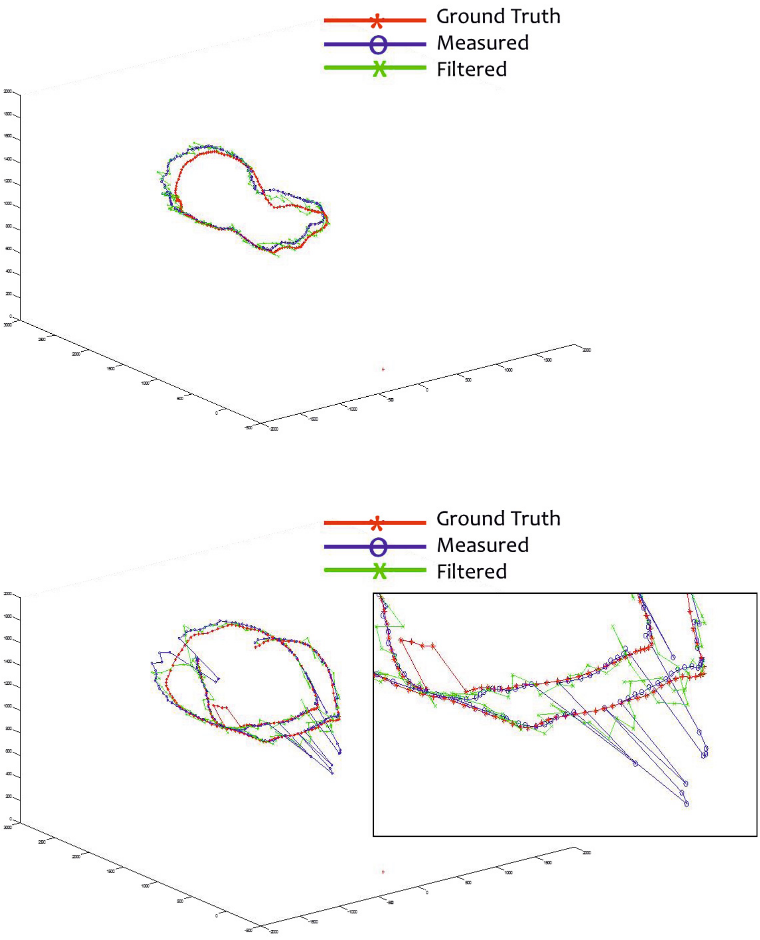

Fig. 8. Relative pose estimation result. (Top) Smooth moving(Stable sensor response), (Bottom) Rapid moving(Unstable sensor response)

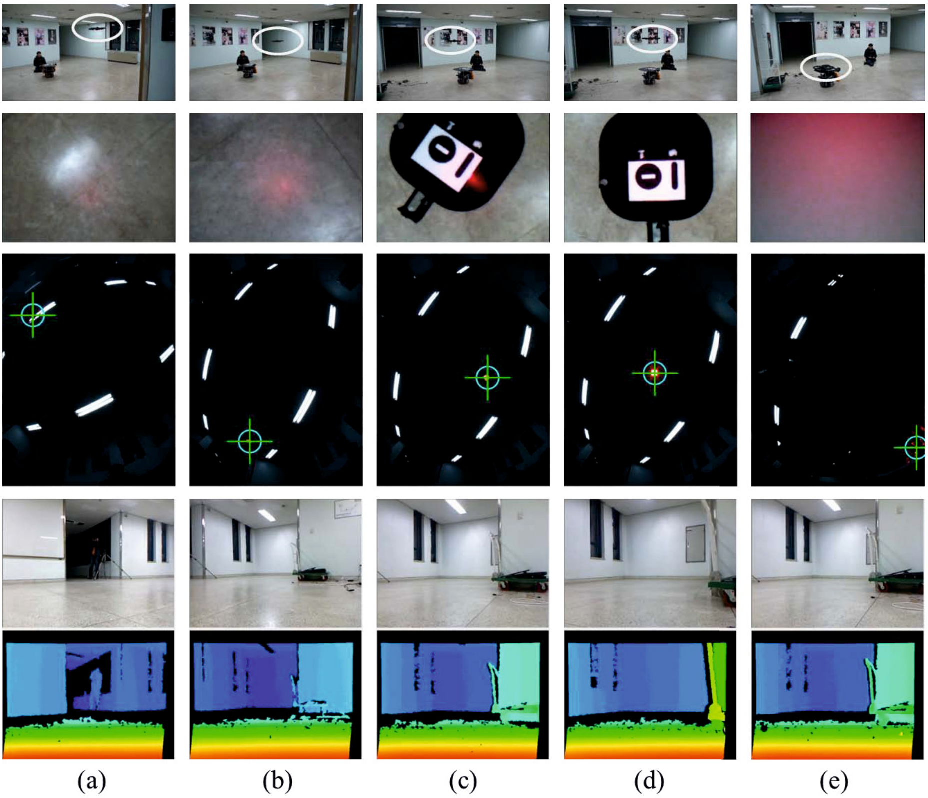

Fig. 9. Autonomous returning-to-base(homing) scenario. Row 1: Captured from external camera. Row 2: Captured by the bottom camera of the UAV. Row 3: Captured by the fisheye camera on the UGV. Row 4 5: Captured by Kinect attached on the UGV. (a) Order to return to base. (b) Moving toward the UGV (c) Pose correction with hovering target (d) Finish correcting hovering target (e) Landing completed.

The ground vehicle can track the relative position and rotation of aerial vehicle with the proposed method simultaneously. So, the integrated system can generate motions for the UAV, which makes the UAV return to the base. Fig. 9 shows the progress of returning to base. In this experiment, the aerial vehicle can return to the base not only the UGV is standing still, but also the UGV is wandering around.

5 Conclusion

We designed an integrated robot system consists of an UGV and an UAV for surveillance service, and proposed a method to estimate the relative pose between two robots using sensor fusion. With a fish-eye camera and an altitude sensor, the relative position between two robots is successfully estiamted. Probabilistic filter made the estimation algorithm robust. To evaluate the performance, a quad-camera stereo capture system is utilized. Also, an autonomous homing scenario is performed to show the possibility of a practical use of the proposed work.

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