Multi-Sensory Motion Estimation and Control of a Mini-Quadrotor in an Air-Ground Multi-Robot System

Tianguang Zhang, Wei Li, Markus Achtelik, Kolja Kühnlenz and Martin Buss

***Abstract*— An air-ground multi-robot system is designed for the purpose of applying bio-inspired sensor-motor modeling on technical systems. It consists of a flying mini-quadrotor equipped with inertial and visual sensors, and a wheeled mini-robot equipped with active markers. The system modules, a multi-sensory pose/motion estimation approach and a closed-loop control of the flying quadrotor are described in this paper. The quadrotor can hover over the ground robot stably and track the ground robot movement. An accurate pose estimation is verified by a comparison between the estimated quadrotor pose and the actual pose during the flight.**

I. INTRODUCTION

We design a heterogeneous multi-robot system, containing a mini-quadrotor and a wheeled mini-robot (see Fig. 1). In this system an accurate 3D pose/motion estimation using multiple sensors is developed and a multi-rate control approach is implemented to enable the quadrotor hovering and tracking the moving ground robot. This testbed can be used to exploit control strategies of a 3D flying system, study various biologically inspired flying behaviors [1], and realize multi-agent applications. Based on [2], this paper describes our improved results of vision/IMU guided mini-quadrotor.

Unmanned Aerial Vehicles (UAVs) are a major focus of active researches, since they can extend our capability in a variety of areas. A significant challenge in developing UAVs is to extract and fuse the useful information in a robust manner in order to achieve a stable flight and an accurate navigation. On-board Inertial Measurement Units (IMUs) are commonly equipped. However, the drift of inertial sensors leads to errors during integration over time, making a steadily accurate estimation of the absolute pose nearly impossible. Therefore, most works rely on an external infrastructures, e.g. GPS for outdoor applications [3] [4] and tracking system for indoor environments [5] [6].

Vision and proprioception are the primary senses to guide the movement. Taking insects as an example, the both senses are important to be fused for localization and motion estimation. They are able to complement the limitations and deficiencies of each other. Digital camera chips and IMU, such as micro-machined gyroscopes and accelerometers, are now available off-the-shelf with good performance, and can provide robust estimates of self-motion as well as 3D scene structure, without any external infrastructure [7].

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Fig. 1. Air-ground multi-robot system

By denying GPS and external tracking system, various techniques are available for UAV control using multi-sensory information [8] [9]. In [10] a novel two-camera method is proposed for estimating the full 6 DOF of a quadrotor. The two cameras are set to see each other. In [11] a monocular on-board camera is set to face a specified moire pattern to get the relative position and orientation of the quadrotor. But the pattern is huge and intricate and the system runs at low rate. An autonomous flight using a monocular on-board camera and IMU is still a big challenge, especially for control of a quadrotor, due to limited field of view and quadrotor flying characteristics: A displacement in a horizontal direction is accomplished by pitch or roll of the body, which results in a large variation of the camera view field.

In this paper, we are aiming at overcoming this challenge. We only use a single on-board camera and IMU to realize fully controlled hovering and tracking. The on-board camera is set to see the ground to get the relative position and orientation between the quadrotor and the markers on the ground robot. Iterative optimization is applied on the pose estimation algorithm. A multi-sensory data fusion is conducted to achieve a more accurate pose and motion estimation. Using this information, both the position and yaw-angle control are achieved in a closed control loop. All the concepts have been verified in real-time experiments.

The remainder of this paper is organized as follows: In Section II, the system overview is introduced. Then, the pose and motion estimation concept based on fusion of IMU and vision data is presented. The controller design is described in detail in Section IV. Experimental results are shown and discussed in Section V. Conclusions and future work are given in Section VI.

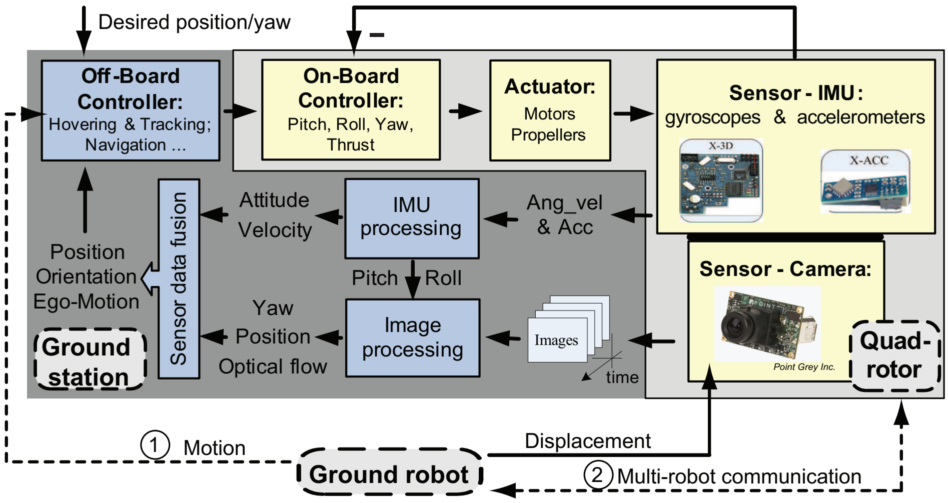

Fig. 2. System overview: The dashed lines show the improvements being developed in progress.

II. SYSTEM OVERVIEW

The entire system consists of three major parts: a quadrotor equipped with multiple sensors, actuators and an on-board controller; a ground robot with active markers; a ground station – a PC with communication and user interface. This is illustrated in Fig. 1 and Fig. 2.

A. Quadrotor

The quadrotor applied in this work is a Hummingbird from Ascending Technologies[1]. The 6 DOF of the quadrotor are controlled by four inputs (roll, pitch, yaw, thrust) by varying the lift forces and the balance of momentum through changing the rotating speed of the rotors. The minimalistic hardware design, i.e. no additional mechanics needed on the fixed-pitch rotors, makes the quadrotor sufficiently robust and dynamically elegant. Moreover, it has no constraints in its omnidirectional flying. There are inertial sensors on-board consisting of three gyroscopes providing the angular velocity of each rotation axis and three accelerometers providing the acceleration along each translation axis. All three axes of rotation (roll, pitch, yaw) are already stabilized by the on-board controller with three independent PD controllers for each angle at a frequency of 1 kHz [5] using inertial sensing information. Although the errors due to time discrete integration are small at the rate of 1 kHz, an external reference is needed to compensate for the drift and to control all 6 DOF of the quadrotor. Considering the limited payload of the quadrotor, a small and light “Firefly MV” from Point Grey Research Inc. is selected as the on-board camera.

B. C’t-Bot with Active Markers

In this air- and ground-based multi-robot system, a mini mobile robot platform named C’t-Bot [12] with a diameter of 12 cm is used to operate on the floor. The robot has two wheels and offers several sensors such as a mouse sensor and simple wheel-encoders for gaining information about its motion. Control of the robot is achieved by programming an on-board Atmel AVR micro-controller or communicating with the ground station.

Two active markers are mounted on a rigid frame on the ground robot and tracked by the quadrotor. They are high-power LEDs covered by table-tennis balls, such that the marker detection in 2D images is more independent from light conditions. More information about marker design and marker detection in 2D input images can be found in [6].

C. Ground Station and Communications

An off-board PC (AMD Phenom 9850, 4GB RAM) is used for image processing, data fusion and execution of the off-board control laws in our application. The input images are transferred to PC via IEEE 1394 currently, while an on-board XBeePro module from MaxStream/Digi[2] transmits IMU sensor data to PC and receives control commands from PC at a rate of 100 Hz wirelessly.

A wireless communication via WLAN is established between the C’t-Bot and the PC as well. All the sensor data such as position and velocity are transmitted and recorded on the PC. A remote control of the mobile robot is enabled.

III. MULTI-SENSORY POSE AND MOTION ESTIMATION

One of the prerequisites of an autonomous flight is an accurate pose estimation. From the quadrotor, inertial data and images can be acquired. The former one contains the angular velocity and linear acceleration. Through merging and integration as well as coordinate transformation we obtain velocity and attitude of the quadrotor with drift. Furthermore, a unique 3D pose can be computed from 2D image data with the help of the attitude value from inertial data. In addition, a data fusion using an Extended Kalman Filter (EKF) improves the accuracy and robustness of 3D pose and self-motion estimation. The information processing structure is illustrated in Fig. 3.

[1]Ascending Technologies multi-robot air-vehicles: http://www.asctec.de

[2]Digi networking solutions: http://www.digi.com

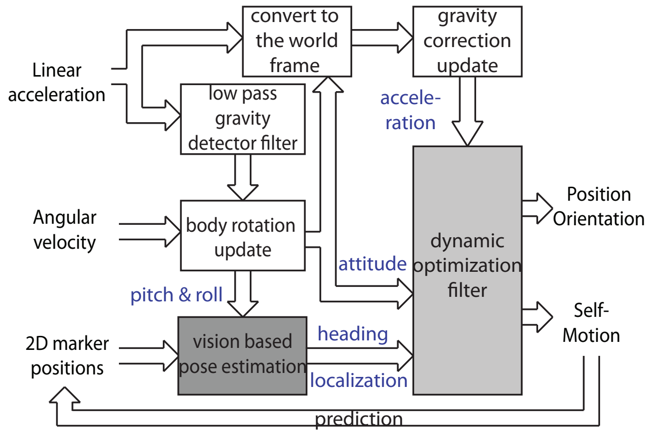

Fig. 3. Multi-sensory data processing and fusion.

A. Frames & Parameters Definition

Fig. 4 shows a scheme of all the frames of reference defined as follows:

- The world frame $\mathbf{S}_w$.
- The object frame $\mathbf{S}_o$ has its origin at the center of two markers. X_o points out the forward direction of the ground robot. Z_o is the vertical axis.
- The body frame $\mathbf{S}_b$ has its origin at the center of the gravity of the quadrotor. X_b points out the nose of the airframe, Y_b points out the right wing, and Z_b points out the belly.
- The camera frame $\mathbf{S}_c$.
- The image frame $\mathbf{S}_i$.

The pose of the quadrotor in the object frame is denoted by

$$_{o}\boldsymbol{x} = (x, y, z, \Psi, \Theta, \Phi)^T$$

with quadrotor position $_{o}\boldsymbol{p}_q = (x, y, z)^T$ and the yaw-angle Ψ, pitch-angle Θ and roll-angle Φ.

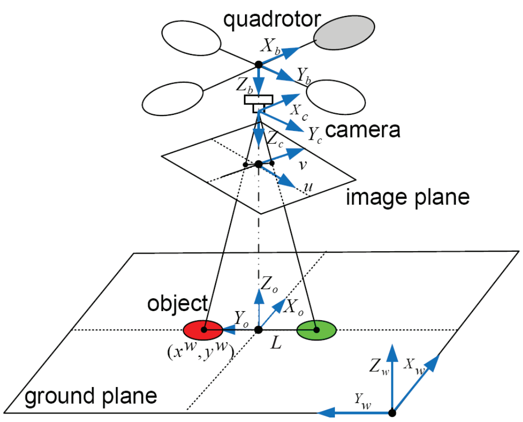

Fig. 4. Frames of reference

B. IMU Information Processing

We modified the framework of the strap-down inertial navigation system introduced in [7]. As shown in Fig. 3, the linear acceleration in the body frame is forwarded into a low pass gravity detector filter. Using this filter, the sudden accelerations are eliminated and the gravity vector remains. Together with angular velocity measured by the gyroscopes, the body rotation in the world frame is updated. Then, the pitch-angle Θ and the roll-angle Φ is obtained. More information about the computation can be found in [5].

Having the attitude and the linear acceleration measured by accelerometers in the body frame, we can compute the linear acceleration in the world frame. After a correction of gravity, the pure linear acceleration in the world frame is obtained. Linear velocity in the world frame is computed through integration of the acceleration.

C. Vision Based Pose Estimation

1) Vision Based Position Estimation: The two markers are mounted on the ground robot with a distance of L. Therefore, the position coordinates of the markers $_{o}\boldsymbol{p}_{1/2}$ in the object frame $\mathbf{S}_o$ have the following values:

$$_{o}\boldsymbol{p}_1 = \begin{pmatrix} 0 \\ -L/2 \\ 0 \end{pmatrix} \quad \text{and} \quad _{o}\boldsymbol{p}_2 = \begin{pmatrix} 0 \\ L/2 \\ 0 \end{pmatrix}. \tag{1}$$

The transformation of marker positions $_{o}\boldsymbol{p}_{1/2}$ from the object frame $\mathbf{S}_o$ via the quadrotor body frame $\mathbf{S}_b$ to the camera frame $\mathbf{S}_c$ can be formalized as follows:

$$\begin{aligned} _{c}\hat{\boldsymbol{p}}_{1/2} &= {}^{c}T_b \cdot {}_{b}\hat{\boldsymbol{p}}_{1/2} \\ &= {}^{c}T_b \cdot {}^{b}T_o \cdot {}_{o}\hat{\boldsymbol{p}}_{1/2}, \end{aligned} \tag{2}$$

where

$${}^{b}T_o = \begin{bmatrix} {}^{b}R_o & {}_{o}\boldsymbol{p}_q \\ 0 & 1 \end{bmatrix}, \tag{3}$$

with $\hat{\{\cdot\}}$ indicating a homogeneous coordinate. The positions of the markers in the camera frame are denoted by $_{c}\boldsymbol{p}_1 = ({}_{c}x_1, {}_{c}y_1, {}_{c}z_1)^T$ and $_{c}\boldsymbol{p}_2 = ({}_{c}x_2, {}_{c}y_2, {}_{c}z_2)^T$. ${}^{b}R_o$ indicates the rotational matrix from the object frame $\mathbf{S}_o$ to the quadrotor body frame $\mathbf{S}_b$, and can be computed using the yaw-, pitch- and roll-angle Ψ, Θ and Φ. The yaw-angle is computed using an iterative estimation algorithm introduced later. The other two angles are obtained from IMU data mentioned in section III-B. ${}^{c}T_b$ is the homogeneous transformation matrix from the quadrotor body frame $\mathbf{S}_b$ to the camera frame $\mathbf{S}_c$ and is known. The position of the quadrotor $_{o}\boldsymbol{p}_q = ({}_{o}x_q, {}_{o}y_q, {}_{o}z_q)^T$ with respect to the ground robot is to be determined.

From the visual information, the 2D positions of the markers in the image frame $_{i}\boldsymbol{p}_1 = ({}_{i}u_1, {}_{i}v_1)^T$ and $_{i}\boldsymbol{p}_2 = ({}_{i}u_2, {}_{i}v_2)^T$ are computed using the algorithms in [6]. Moreover, a predicted search window based on the previous motion estimation is applied in 2D input images to reduce computational cost (see Fig. 3). According to the pinhole camera model with a focal length λ, the following relation can be easily derived:

$$_{i}\boldsymbol{p}_{1/2} = \left(-\frac{{}_{c}x_{1/2}}{{}_{c}z_{1/2}} \cdot \lambda \quad -\frac{{}_{c}y_{1/2}}{{}_{c}z_{1/2}} \cdot \lambda\right)^T. \tag{4}$$

Substituting ${}_c\boldsymbol{p}_{1/2}$ in (2) and (4), we have four equations for three unknown variables of ${}_o\boldsymbol{p}_q$. Using least-square method, ${}_o\boldsymbol{p}_q$ is found and used for quadrotor control.

For the further experimental evaluation, the absolute quadrotor position ${}_w\boldsymbol{p}_q$ is computed as follows:

$$ {}_w\hat{\boldsymbol{p}}_q = {}^wT_o \cdot {}_o\hat{\boldsymbol{p}}_q, \tag{5} $$

where ${}^wT_o$ is obtained using the ground robot pose feedback with respect to the world frame S_w.

2) Iterative Optimization: Since the yaw-angle Ψ cannot be directly determined from image data, we use the gradient descent algorithm to estimate yaw-angle iteratively.

Firstly, a prior yaw-angle Ψ^- is computed using image data containing the 2D marker positions ${}_i\boldsymbol{p}_{1/2} = ({}_iu_{1/2}, {}_iv_{1/2})^T$ as follows:

$$ \Psi^- = \operatorname{atan2}\big(({}_iv_2 - {}_iv_1), ({}_iu_2 - {}_iu_1)\big), \tag{6} $$

Then, we use the pitch- and roll-angle Θ and Φ as well as Ψ^- to compute a prior rotational matrix ${}^bR_o^-$ and a prior quadrotor body position ${}_o\boldsymbol{p}_q^-$ as described above.

After that, we use ${}^bR_o^-$ and ${}_o\boldsymbol{p}_q^-$ to compute 2D marker positions ${}_i\boldsymbol{p}_{1/2}^-$ and compare ${}_i\boldsymbol{p}_{1/2}^-$ with ${}_i\boldsymbol{p}_{1/2}$. The gradient descent algorithm is used here to find an optimal Ψ^* iteratively, until ${}_i\boldsymbol{p}_{1/2}^- \approx {}_i\boldsymbol{p}_{1/2}$. Concurrently, the quadrotor position ${}_o\boldsymbol{p}_q$ is optimized as well.

It is worth to mention that this iterative optimization method used here is very computationally efficient and, therefore, does not impair the total computational performance.

D. Multi-Sensory Data Fusion

Vision sensor and IMU have their own advantages and drawbacks, which are nevertheless complementary to each other. For quick motion, IMU is accurate and sensitive, whereas vision sensor is not adequate due to relatively low frame rate and limited bandwidth. Motion blur in input images also causes large uncertainty. In contrast, for slow motion, IMU has unavoidable measurement uncertainty, while vision sensor is more accurate. Moreover, IMU can facilitate a unique vision based position estimation as mentioned in Section III-C, while vision data can help IMU distinguish a change in inclination from body acceleration.

In Section III-B we compute the linear acceleration and velocity as well as the attitude in the world frame (also in the object frame) from IMU data, while in the Section III-C we obtain the position, heading and their variation rate in the object frame from visual sensor data. They are partly overlapped and should be fused together, in order to achieve a more accurate estimation of the quadrotor's pose and self-motion.

An extended Kalman filter [13] is used here for the sensor fusion and system state estimation. The system process equation is formulated as follows:

$$ \boldsymbol{x}_k = \boldsymbol{f}(\boldsymbol{x}_{k-1}, \boldsymbol{u}_{k-1}) + \boldsymbol{\omega}_{k-1}, \tag{7} $$

where the components of $\boldsymbol{x}_k$ are quadrotor position, orientation and translational velocity in the object frame at time step k:

$$ \boldsymbol{x}_k = ({}_o\boldsymbol{x}_q, {}_o\dot{\boldsymbol{p}}_q)_k^T. \tag{8} $$

Similar to the algorithm described in [14], the velocity and the acceleration measured by IMU are regarded as system input $\boldsymbol{u}$ and used to drive the prediction step. The visual data is used in the correction step.

The observation equations are formulated as follows:

$$ \boldsymbol{z}_k^v = \boldsymbol{h}^v(\boldsymbol{x}_k) + \boldsymbol{v}_k^v. \tag{9} $$

where $\boldsymbol{z}_k^v = ({}_o\boldsymbol{p}_q, \Psi)^T$ is the measurement from vision sensor.

In (7), $\boldsymbol{\omega}_{k-1}$ indicates the process noise, while $\boldsymbol{v}_k^v$ represents the measurement noise due to vision sensor in (9). They are empirically determined. A small angle approximation is used to simplify the Jacobian matrix computation of partial derivatives of $\boldsymbol{f}$ with respect to $\boldsymbol{x}$. To deal with the synchronization problem between IMU and camera information, an integration of the high-frequency IMU data over a time τ is added to the vision data. τ is approximately $50\ ms$, indicating the time interval between a real visual data input and the fusion time point, which is measured and determined in offline experiments.

After this multi-sensory fusion, more accurate position, orientation and velocity informations are achieved.

IV. SYSTEM CONTROL

A. Preliminary Controller Design

To achieve the desired position and yaw-angle of the quadrotor relative to the ground robot, the quadrotor position ${}_o\boldsymbol{p}_q$ and the yaw-angle Ψ in the object frame should be controlled with the help of an external reference, namely the markers on the C't-Bot.

As mentioned in Section II-A, the interface of the quadrotor offers the following input signals to control the rotors:

- Roll : roll-angle $\Phi \Rightarrow$ acceleration to left or right;
- Pitch : pitch-angle $\Theta \Rightarrow$ acceleration forwards or backwards;
- Thrust : momentum of motors $F \Rightarrow$ acceleration in the vertical direction;
- Yaw : angular velocity $\dot{\Psi}$ around the vertical direction.

The acceleration commands are transformed into appropriate control commands for the quadcopter. In the current implementation, it is a linear block for small angle approximation. For simplicity, couplings between the four channels are ignored. These four input signals are controlled by 1 kHz on-board controllers (see Fig. II). As no dynamic or aerobatic maneuvers should be performed at the current step, the control inputs are assumed to be linear to the resulting accelerations.

Four off-board position controllers are implemented independently: three PID-controllers for position ${}_o\boldsymbol{p}_q$ as well as a PI controller for yaw-angle Ψ. They build a multi-rate control loop with the on-board controller together. The actual position and yaw-angle are provided by the data fusion at 100 Hz due to the wireless communication between the quadrotor and the ground station.

B. Compensation of the Time Delay

Time delay in the control loop can lead to oscillation. To compensate the undesired time delay a state predictor is employed. It's reasonable to assume that the 3D position of the quadrotor is a second-order function of the time: $s = a \cdot t^2 + b \cdot t + c$, where s is the position of quadrotor in the world frame. The last n estimated states are used to determine this function and parameters a, b and c are expected to stay constant in this time window. This structure of the predictor has also another advantage: high frequency shaking of the estimation is filtered out.

C. Improvement by Velocity Compensation

The quadrotor is able to hover with the controllers described above. We improve these results by using the data of the on-board IMU, which provide inertial measurements at a rate of 100 Hz. The estimated velocity in world frame is considered as another differential term and weighted by a negative constant factor and added to the control commands sent to the quadrotor every 10 ms. By estimating the speed of the quadrotor with these sensors, we achieve better damping of the oscillations at higher P-terms and faster responses to disturbances.

V. EXPERIMENTAL EVALUATION

A. Ground Truth and System Calibration

To evaluate the pose estimation and control performance, we use a position and motion sensing system called Visualeyez[3] *VZ-4000*, which can record the 3D positions of four markers mounted on the quadrotor frame. A similar quadrotor pose calculation used in [6] is conducted and regarded as the ground truth of the actual flying trajectory and heading. Based on the ground truth from the tracking system and quadrotor pose estimation using our algorithm, a system calibration of coordination transformation between quadrotor, ground robot and tracking system is accomplished.

B. Hovering

Fig. 5 shows the position and yaw-angle of the hovering quadrotor. The desired position for hovering is 1.2 m over the markers and the desired yaw-angle is the ground robot forward-moving direction (the dash-dotted lines). The experiment results show that the quadrotor can hover around the set position with oscillations. The maximum position errors in the x-, y- and z-direction are smaller than 0.2 m, while the maximal error of yaw-angle is about $5°$.

The flying trajectory measured by *VZ-4000* is regarded as the ground truth (the stars) for evaluation of the pose estimation result. The difference between ground truth and the estimation is the pose estimation errors using the fused IMU/vision information. The estimation error in x-direction is shown in Fig. 6. The maximum estimation errors in x-/y-direction and in z-direction are about 0.05 m and 0.10 m respectively, while the yaw-angle estimation error is under $2°$. Apparently, the pose estimation is very accurate.

[3]PhoeniX Technologies Incorporated: http://www.ptiphoenix.com

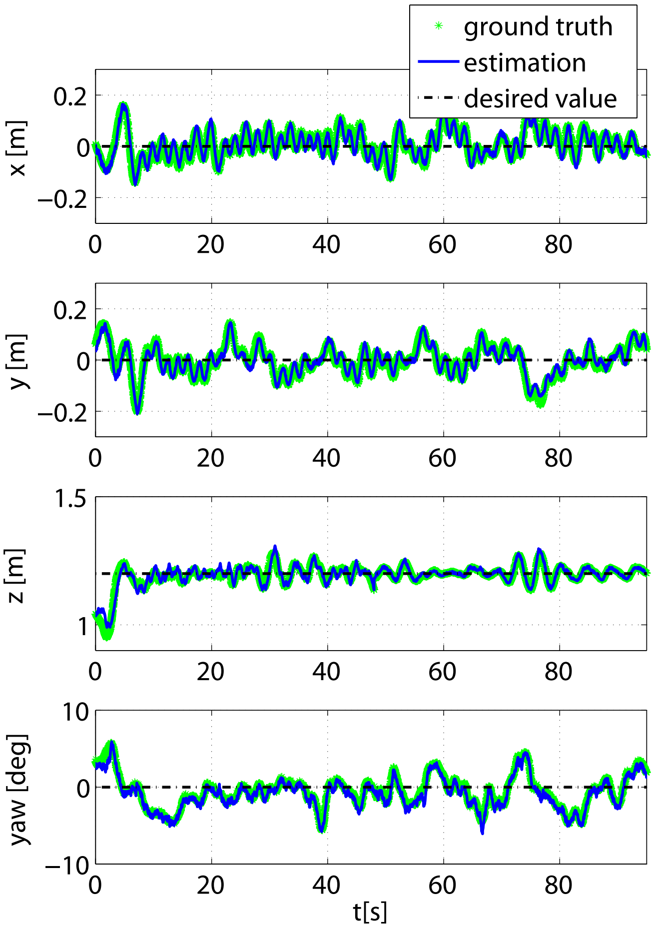

Fig. 5. Quadrotor hovering performance

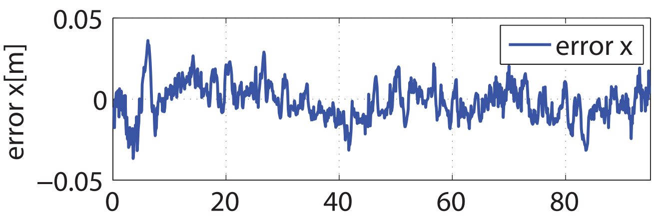

Fig. 6. Estimation error in x-direction

C. Tracking the Ground Robot

In the tracking experiment, the C't-Bot has moved along a square with a side length of 0.8 m approximately. During the movement, pure translation, pure rotation as well as simultaneous translation and rotation were exhibited by the C't-Bot. Fig. 7 illustrates the results of quadrotor tracking the moving C't-Bot: the position and the yaw-angle. The thick solid lines show the desired quadrotor trajectory according to C't-Bot movement, namely 1.2 m directly over the C't-Bot. The light thin solid lines are the actual flying trajectory measured by *VZ-4000*. The maximum control error in the

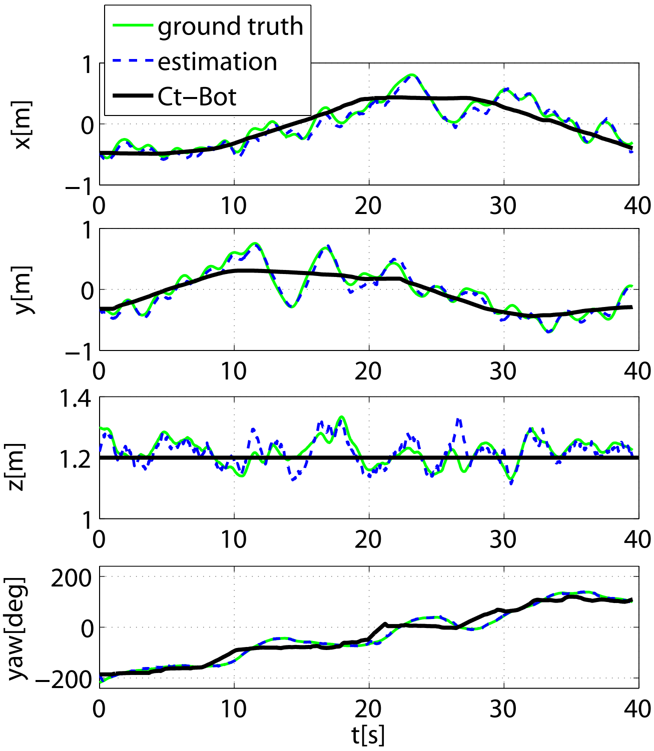

Fig. 7. Experimental result of tracking the C't Bot

x/y-direction is about $0.4\ m$, while the maximum error in the z-direction is about $0.15\ m$. The maximum yaw-angle error is about $25°$.

The pose estimation using the IMU/vision fusing algorithm is illustrated using dashed lines, which are very similar to the actual trajectory measured by the tracking system, namely the light thin lines.

A video of the results can be seen at the authors website[4]. A fishing rod is used to tether the quadrotor and hold the cable between camera and PC. During the quadrotor flying over the ground robot, the cable is always loose and exerts no force on quadrotor. Only when the control is failed, it ensures the quadrotor against damage. The accompanying video shows both the hovering and the tracking performance in simulations using a model from BYU [14] and in real-time experiments.

D. Discussion

The oscillation around the set-point is probably due to the large time delay in the control loop and the prediction error. To achieve an improvement of the flying performance, an on-board computation with mini operation system and a more accurate predictor are considered. Other active/adaptive control strategies such as back-stepping or sliding mode are proposed as the next step of our work.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, a visual/inertial multi-sensory system is developed and implemented for real-time control of a mini-quadrotor in an air-ground multi-robot system. An efficient pose and motion estimation is proposed and further optimized. Synchronized measurements from multi-sensor are fused to improve the estimation accuracy. Thereby, the limitations and deficiencies of each sensor are complemented. Furthermore, a multi-rate control structure is proposed. A quick system response based on the fast on-board IMU feedback and an accurate correction of pose estimation based on relatively low-frequency data fusion are obtained. Real-time experiments are successfully conducted to verify the performance of the algorithms. Future directions are: ground robot motion feedback for quadrotor control; and communication between the quadrotor and the ground robot.

[4]http://www.lsr.ei.tum.de/team/zhang/ROBIO2009zhang.mpg

VII. ACKNOWLEDGMENTS

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