ENHANCING SENSOR CAPABILITIES OF WALKING ROBOTS THROUGH COOPERATIVE EXPLORATION WITH AERIAL ROBOTS

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Georg Heppner, Arne Roennau, Ruediger Dillman

Abstract:
Mobile robots can be used to support humans in many applications ranging from simple process automation to complex autonomous inspection tasks. While walking robots are perfectly suited to cross rough terrain, they are not able to detect everything in their environment as certain areas might be occluded or too far away. This paper presents a method of enhancing the sensor capabilities of the walking robot LAURON IVc with the use of the lightweight aerial robot ARDrone. A simple method for localization of the ready to use UAV is presented using only color tags and the motor encoders of LAURON. The combination of these two robot types enhances the sensor range of LAURON greatly, while the ARDrone gains localization information from LAURON that acts as a base station.

Keywords: *walking robot, aerial robot, Lauron, cooperative exploration, low cost sensors, UAV, ARDrone*

1. Introduction

Mobile robots can support humans in a wide range of different applications. Inspection tasks that would otherwise be costly or impossible become more efficient or are enabled with the help of autonomous or teleoperated robots. Especially in hazardous environments where humans can not or do not want to work, i.e. the search for survivors in a building close to collapse mobile robots can be used without the need to endanger humans. Off the wide variety of robots, walking robots like the hexapod LAURON IVc (Fig. 1) are the ones best suited for such rough environment. They offer great flexibility because they can work on almost any terrain and under bad conditions while carrying a considerable payload. The biggest drawbacks of walking robots are their limited walking speed and camera position which is very close to the ground. When operating in rough areas it is imperative to choose regions of interest well and try to plan optimal paths to maximize the efficiency of the robot. The low point of view however can easily be obstructed by larger objects such as boulders or even a table. This can lead to non optimal paths, as not all the areas can be observed by the robot. Vital information in search and rescue scenarios, like the position of a person, could be missed because of these obstructions. The robot could walk around obstacles to explore the whole area, use special sensors like an infrared camera to see through some obstacles or special mounts to get a better point of view for its camera. But these options are time consuming, reduce the amount of payload that can be carried or constrain the freedom of the robot design and may lead to an unsatisfactory system performance. Creating a map of the environment or locating certain features or objects also requires spatial information. This is usually gathered by using 3D sensors like moving laser scanners or structured light cameras. While these sensors deliver good results, they are often expensive, have difficulties under some specific conditions like bright light or are just not available on every robot due to weight or power restrictions.

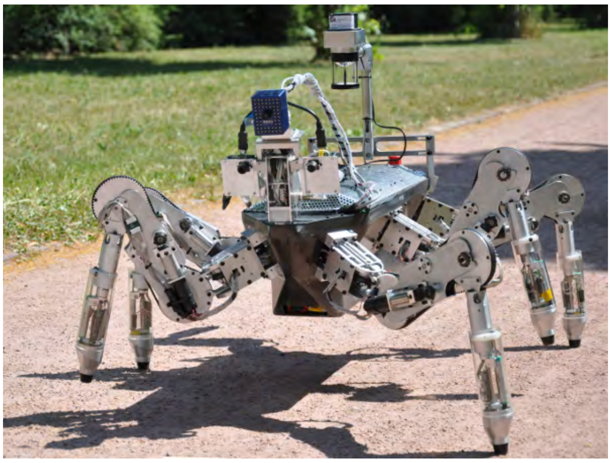

Fig. 1. *Bio-inspired six legged walking robot Lauron IVc: versatile platform for exploration and search and rescue*

Another approach of overcoming the sensor boundaries of mobile robots ist the use of several cooperative robots to explore the area [8]. Aerial robots (UAV = Unmanned Aerial Vehicle, or MAV = Micro Aerial Vehicle) in combination with ground robots have gained growing attention from researchers in recent years [10, 13, 14] as they complement each other very well. They are fast, small, agile and provide a high point of view that can cancel out the sensoric weaknesses of ground robots. A main challenge is the localization of the UAVs for control and to gain spatial information about detected features. Sophisticated UAVs use onboard sensors like laser scanners [3] or complex vision algorithms [7]. UAVs capable of such task however are also very expensive and can therefore not be used in every application.

The ARDrone from Parrot [1], which was produced as a sophisticated toy, is a cheap alternative that has enabled the use of UAVs for a broader range of applications [6]. As no onboard computing can be done the position has to be captured by the ground robot. This is often achieved by using stereo geometry [4] or even motion capture systems [9] if the main focus are novel algroithms. For mobile robots complex sensors like laser scanners or a calibrated stereo cameras may not be available. When no such hardware is available either complex markers, precise marker placement [5] or special constructions like a frame of LEDs [12] were suggested. These approaches reconstruct the pose of an aerial vehicle solely out of camera data which requires a clear image and exact knowledge about the sizes and placement of the markers.

In this paper we want to present a way to use the cheap ARDrone to complement the sensors of LAURON without the use of any special hardware or extensive preparation. We present a very simple method to localize the ARDrone with already available on board sensors of LAURON using visual markers at the UAV and LAURON's encoder information of the head pan tilt motors. By using their sensors, we can detect the position of the UAV and in turn use its location to find otherwise occluded information in the area which greatly enhances the sensor capabilites of LAURON.

The paper is structured as following: In Section 2 we present the robots and their main features used for this experiment as well as our approach to localize the UAV. Section 3 provides results regarding accuracy of the proposed method and section 4 gives a summary of the results as well as an outlook for future applications.

2. Approach

For this paper we used our six legged walking robot LAURON IVc in combination with the commercially available ARdrone from Parrot.

2.1. LAURON IVc

Inspired by the stick insect, the six legged walking robot LAURON IVc (Fig. 1) offers 3 degrees of freedom in each leg and 2 additional ones on the head. With these overall 20 degrees of freedom and a wide range of sensors LAURON is a versatile platform for exploration, search and rescue and inspection tasks. Equipped with 2 dragonfly cameras, as well as a 360 degree camera and a time of flight camera LAURON has various ways to perceive its surroundings. The legs are spring dampened and equipped with current-, contact- and force-sensors to ensure a reliable foothold and optimal stability in every terrain. The two cameras and the ToF camera are mounted on a articulated head that can be panned and tilted. High precision encoders in every joint ensure reliable positioning and allow the user to know where LAURON is looking. A more detailed description of the robot in general and its control system can be found in [11].

2.2. Parrot ARDrone

The ARDrone from Parrot is a commercially available quadrocopter for ca. 300 Euro. Made out of a carbon fiber frame with a foamed plastic body and protection ring, the lightweight UAV comes ready to use for end-users. Four brushless motors are controlled by the integrated circuit board which also offers two cameras to send over wlan: one pointing straight ahead, the other pointing down. The downwards pointing camera is used to stabilize the UAV by calculating its speed with the help of optical flow. An ultrasonic rangefinder is used to constantly measure and hold the height during flight. The ARDrone can fly for about 12 minutes on full batteries and reach speeds of 5 m/s. It is controlled by a remote PC which only needs to send directional commands like forward speed, while the control of the individual motors and the stabilization of the UAV is done by an onboard flight controller. A public API enables the user to access navigational data and send movement commands but the behavior of the controller as well as the full camera resolution can not be accessed.

Fig. 2. *Parrot ARDrone is a ready to use quadrocopter*

2.3. Cooperative Exploration

The capability of walking robots to traverse very rough terrain comes with the price of reduced speed. Under normal conditions this is not an issue as LAURON can operate autonomously for about an hour, even longer with an additional mobile power source. When exploring large spaces however it would be desirable to have a way of deciding which areas are of interest before LAURON even starts to move in a certain direction. Especially for trajectory and mission planning the knowledge about traversable paths is important. Because of its low point of view LAURON may not survey the whole area ahead as there will be occlusions. Far away objects are also hard to classify in advance as the cameras mounted on LAURONs head can not zoom their lenses during use.

The ARDrone on the other hand can fly in narrow spaces and reach high speeds. With the view from above many occlusions can be avoided at once while others can be explored quickly by the robot. As the ARDrone does not have any laser scanners or other sensors for 3D self localization the movement in small spaces is a problem. The flight time of around 12 minutes prohibits longer exploration tasks as they can be performed by LAURON.

Our approach for enhancing the sensor capabilities of LAURON is therefore to combine the benefits of these two systems and cancel out some of their weaknesses. LAURON offers a good landing spot for the ARDrone on its back. The UAV adds only a total weight of $420g$ to LAURON which does not influence the walking behavior at all. If LAURON needs addi-

Fig. 3. *ARDrone landed on the back of LAURON IVc. Vital energy can be saved for the next assignment*

tional information about its surroundings the UAV can take off from its back and explore the unknown regions. By tracking the UAV during its flight with a visual marker, we are able to determine its relative position as a three dimensional offset from LAURON. The UAV can be guided towards unknown spots in LAURON's field of view and complement the information about the environment. After the exploration of unknown or interesting spots is complete, the UAV can be guided back to LAURON where it can land to save energy for its next assignment.

LAURON uses the MCA2 [15] software framework, while the ARDrone is controlled with the ROS (Robot Operating System from Willow Garage) [2]. They can communicate using the Rosbridge package in ROS with an additional client implementation in MCA2. Rosbridge allows client applications to send and receive JSON formatted messages via a TCP socket which will in turn be published or subscribed as ROS Topics. By using this adapter the two robots can communicate without further changes to either of the frameworks.

2.4. Localization of ARDrone

To control the UAV accurately and identify the surrounding with spatial coherence it is important to know the position of the aerial robot. Because of the ARDrone's limited payload and the closed hardware, attaching additional sensors for localization is costly. Without the ability to use the ARDrone's onboard computer for visual odometry we chose the already available cameras of LAURON for external tracking of the UAV. Although LAURON could use stereo vision to track the UAV we chose to use only one camera as this would be available on almost every robot.

The detection of the UAV's position was implemented using a visual servoing approach. Markers were added to the outer frame of the ARDrone (see red/green spot in Fig. 3). To detect this marker the camera image of LAURON is transformed into the HSV color space. A threshold analysis searches for the marker and calculates its center point (Fig. 5). Multiple thresholds were defined to detect the UAVs marker under various lighting conditions. The number of detected pixels is used to calculate a confidence value for the detected center position. Once this value exceeds the pre defined confidence threshold LAURON follows the UAV with its camera. The head movement is controlled by a PD-controller. If the detected marker resting in the center of the camera image the joint encoders can be used to extract the angles in which the ARDrone is detected. As we are only using one camera the depth information can not be recovered from this information alone. The ultrasonic range sensor of the ARDrone is used to measure its height (h) above the ground. Using the pan and tilt angles α, β and the height of the UAV h the position x_c,y_c,z_c in regard to LAURONs camera can be recovered (Fig. 4) with the simple equations:

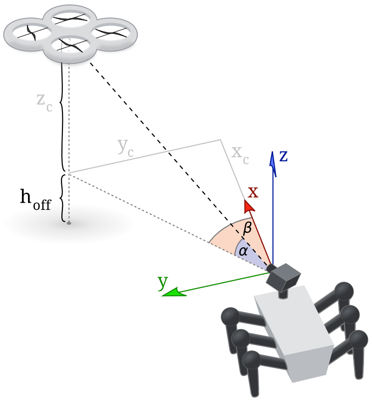

Fig. 4. *Diagram of the angles and distances used in the simple tracking calculations. Lauron follows the UAV visually, measures the angles α and β with its head encoders and combines them with the height measured by the UAV for a 3D offset*

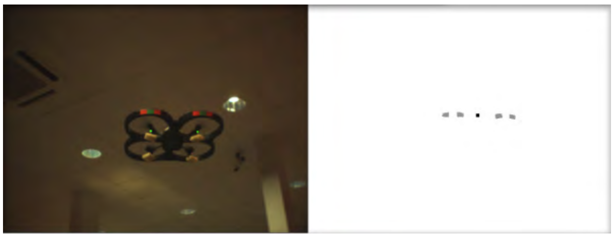

Fig. 5. *LAURONs view of the ARDrone. The input image (left) and the detected marker positions (right) with the marked center (darker central dot). If the detected marker moves out of LAURONs field of view it follows with its head until the marker is centered again*

$$z_c = h - h_{\text{off}} \tag{1}$$

$$d' = \frac{z_c}{\tan(\alpha)} \tag{2}$$

$$y_c = d' * \sin(\beta)$$
$$y_c = z_c * \frac{\sin(\beta)}{\tan(\alpha)} \tag{3}$$

$$x_c = d' * \cos(\beta)$$
$$x_c = z_c * \frac{\cos(\beta)}{\tan(\alpha)} \tag{4}$$

The height of the UAV (h) is modified by the offset h_{off} which is the distance from the camera of LAURON to the ground. Also the resulting coordinates give the relative distance in regard to the camera position (coordinate system in Fig. 4) which has to be transferred into LAURONs base coordinate system (shown in Fig. 6). The orientation of the UAV is not gathered by this approach as it is not strictly necessary for the sensor enhancement of LAURON. In a later stage however, it could be added by using more than one tracker or by always facing the ARDrone towards LAURON with the same tracking algorithm.

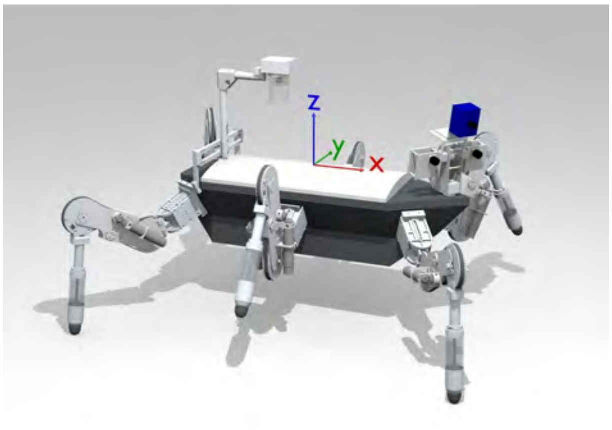

Fig. 6. Body coordinate system of LAURON IVc

If LAURON does not find the ARDrone after liftoff the head is moved in a search pattern until the marker is found again. The used Dragonfly cameras offer a framerate of 30 frames per second. As the marker detection is not computational expensive the onboard PC can calculate the position well within the time of one frame. Using this technique we are able to track the UAV reliably and calculate its position as long as the marker is visible.

2.5. Control of the ARDrone

Because the focus of this work was the tracking and the general usability of the system, the UAV movements are currently controled by a human operator with a gamepad. The takeoff from laurons back is trivial as the UAV just has to fly upwards and forward for a short period of time. The landing on the other hand poses a serious challenge for the operator as the downwash and a tight landing spot require a quick and precise action. To make this procedure easier and enable a fully autonomous landing at a later stage we are using a simple marker on LAURONS back (Fig . 7) for an automatic landing procedure. In order to start the landing procedure the ARDrone needs to hover over the marker at a certain height. Once the procedure is active an internal marker tracking of the ARDrone holds the position while slowly descending. A drawback of this system is, that the marker can only be used at relative close range and does not yet provide orientation information.

3. Evaluation

The communication of the two robots using Rosbridge worked very well. Without major modification to the individual frameworks data could be send without large time delay. Only the visual markers that come with the ARDrone had to be applied to the UAV. For easy testing of the UAV take off capabilities the 360 degree camera of LAURON was detached. In the future, a small landing pad could be added on top of the camera or any other place.

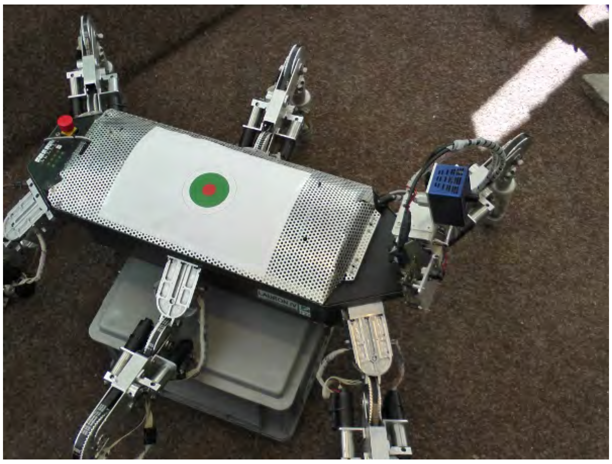

Fig. 7. Marker on LAURONs back used for landing. Once the ARDrone has detected the marker it holds its position while slowly descending

As a first test a search and rescue scenario was build (Fig. 8) and explored by the robots. LAURON was not able to see the child doll behind the large boulder (Fig. 10a) from its startpoint. Of course LAURON is able to reach the child, but has no incentive to do so as no information about the occluded area is present. The ARDrone was launched from LAURONs back and flown manually over the unknown area (Fig. 9) where it is able to detect the child (Fig. 10b).

Fig. 8. Test environment that resembles the wake of a natural desaster. The environment is filled with rubble and large objects block the view of LAURON

The tracking of the UAV worked well, even under varying ligthing conditions. In Fig. 5 the markers are clearly visible although LAURON looks directly at the ceiling lights. One problem was the distance in which the markers where being detected. Although the markers could easily be recognized up to 6 meters

Fig. 9. *LAURON is tracking the UAV which explores the area by tilting and panning its head*

(a). LAURON's view of the child is obstructed by a large boulder

(b). View from the lower camera of the ARDrone. The UAV is able to look behind obstacles and provide unique viewpoints

Fig. 10. *Different viewpoints of LAURON and the ARDrone*

the confidence value of course dropped as less pixels where detected. This could be compensated by using the detected distance to alter the detection. If for example the UAV is detected to be very far away, the confidence threshold needed for acceptance of the pattern could be lowered.

The localization quality was evaluated in several ways. To determine the quality of the detected positions several positions were accurately measured by hand with a laser rangefinder. The tracking was then used to detect the ARDrone that was placed manually at the predefined positions several times in a row. As the height of the ARDrone might have a significant impact on the results, the same positions were measured aggain only using one of the markers without the UAV and a a simulated height. Table 1 and 2 show the results for the simulated height in 2 meter and 4 meter distance from LAURON. The mean errors of the positioning in regard to the ground truth are given in mm for the x,y and z position of the UAV. To verify different influences the positions where measured in 1 m, 1.50 m and 2 m height as well as with an y position of -50 cm, 0 cm and +50 cm.

It becomes clear that the heigth of 1 meter produces the least accurate results. This is easily explained through the formulas. The calculation of x_c (equation 4) as well as y_c (equation 3) use $\tan(\alpha)$. If α becomes too small no acurate result for the distance can be given. This is logical as we only have 2 measurments for a 3 dimensional position when α becomes zero. Although this influences the results very strongly, having a position error of 18 cm at 2 meters and 84 cm at 4 meters in the worst case will still produce useful information. The UAV was meant to fly higher than the ground robot anyway which leaves the more realistic cas of 1.5 meter flying height. In this height the results are much more precise with a maximum error of 5 cm at 2 meter distance and 60 cm at 4 meter. The same positions where tested again with the real sensor information of the ARDrone, the results are given in table 3 and 4

	-50 cm	0 cm	+50 cm
1 m	149/6/0	117/23/0	185/16/0
1,5 m	10/6/0	5/41/0	51/23/0
2 m	71/13/0	56/30/0	120/63/0

Tab. 1. *Results (x/y/z error in mm) in 2 meter distance (x) from LAURON with simulated height, left:height of marker, top=relative y position*

	-50 cm	0 cm	+50 cm
1 m	843/143/0	717/114/0	828/25/0
1,5 m	412/70/0	625/110/0	292/98/0
2 m	550/14/0	174/157/0	207/160/0

Tab. 2. *Results (x/y/z error in mm) in 4 meter distance (x) from LAURON with simulated height, left=height of marker, top=relative y position*

	-50 cm	0 cm	+50 cm
1 m	507/140/118	876/11/175	724/94/61
1,5 m	238/101/126	248/25/104	239/3/94
2 m	100/60/78	83/14/97	145/58/111

Tab. 3. *Results (x/y/z error in mm) in 2 meter distance (x) from LAURON with measured height, left=height of marker, top=relative y position*

	-50 cm	0 cm	+50 cm
1 m	1260/200/84	2970/30/334	1286/180/182
1,5 m	742/179/98	699/85/107	720/23/134
2 m	439/198/99	428/117/101	395/48/108

Tab. 4. *Results (x/y/z error in mm) in 4 meter distance (x) from LAURON with measured height, left=height of marker, top=relative y position*

The results are again bad at a lower height. Ultrasonic rangefinders, as used by the ARDrone for height control, can have great differences in measurement. Nevertheless the results show that an almost constant offset was measured. As the premise was to test the ready to use UAV, this value was not calibrated which explains the constant offset. This could easily be fixed to improve the results. Even without a proper calibration, a maximum error of around 70 cm in x direction and only 20 cm in y direction at 4 meter distance is still quite good.

In order to tests the behavior of the system while the UAV is moving a simple flight pattern was recorded and is shown in Figure 11. All values are given as positions in the head coordinate system. The ARDrone

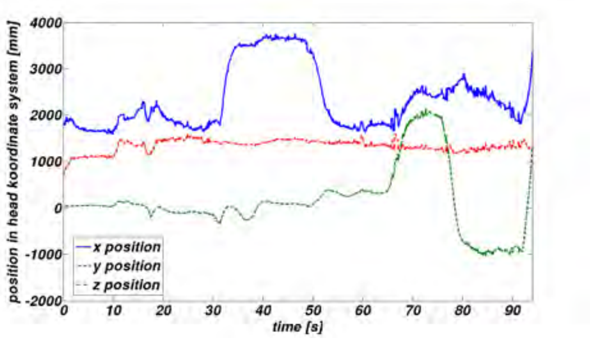

Fig. 11. *Position of the UAV as measured by LAURON. Positions are given in head koordinate system*

was started at a distance of 2 meters from LAURON. A height of 1.8 meter was measured using a laser rangefinder. After a short hover period the ARDrone was moved back to a spot 4 meters away from LAURON where it hovers aggain and then returns to the initial position. From this position the UAV is steered left (as seen from Lauron) for 1.6 meters and after a short hover period about 80 centimeters to the right of the center position. After a return to the center the UAV lands.

Several inaccuracies produce the failure in the position results of the measurement. LAURONs camera has only a limited resolution of 640x480 pixel which limits the acuracy of the marker detection. After detecting the marker the head is moved by a PD-controller which is disabled after reaching a certain threshold area around the center point. Also the head mounting of the camera can be off which leads to an error of up to an degree in the angle determination.

4. Conclusions

In this paper we presented the use of a lightweight UAV as a tool to enhance the sensing capabilities of the walking robot LAURON. Even though the positioning results show an error between 4 cm and 80 cm the overall performance of the system is very good. When detecting features in the environment an offset of 80 cm is no problem as the ground robot can investigate it in more detail later on. The combination of a lightweight aerial robot and a ground robot as base station has proven to work well. We were able to track the position of the UAV and therefore of interesting features in the area without the need for special or expensive equiptment. The first attempts for automatic landing are also very promising and enable the ARDrone to repeatedly land on LAURONs back.

Without the need for additional expensive or heavy hardware the proposed system comes as an almost ready to use enhancement of the already available sensors of the walking robot LAURON IVc. The setup offers room for further improvements regarding the used sensors on LAURON as well as the ARDrone. In the future we want to make use of this system as a full featured sensor of LAURON that can be used at any time. By using dead reckoning navigation as an enhancement for the ARDrone we will be able to fly autonomously or guided by LAURON. We also want to look into a way to automatically combine the information gathered into one representation of the sorroundings. By combination of external tracking, dead reckoning navigation and marker tracking we want to enable the team of UAV and ground robot to autonomously perform the search actions we carried out by hand and therefore enhance their sensor capabilities for autonomous actions.

AUTHORS

Georg Heppner* - FZI - Research Center for Information Technology, department IDS - Interactive Diagnosis- and Service Systems, Haid-und-Neue-Str. 10-14, Karlsruhe, Germany, e-mail: heppner@fzi.de.
Arne Roennau - FZI, IDS, e-mail: roennau@fzi.de.
Ruediger Dillman - FZI, IDS, e-mail: dillman@fzi.de.

*Corresponding author

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