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Abstract—Traditionally, UAVs and Mobile Robots are viewed as two separate entities. However, upon closer examination of their synergies, a more unified conception of a closely-coupled system of the two could easily justify a view where both are just seen as separable parts of the body of a unitary hybrid symbiotic system – essentially, one robotic entity, whose body parts can separate temporarily, and get together again later. In this paper, we will describe a prototype system consisting of a small-scale indoor pilot version of a much larger outdoors full-scale system, as an illustration of this concept. Such indoor pilot versions have multiple advantages, as we shall show. In our prototype, a mobile robot UGV serves as a transport as well as recharge station for a lightweight quad-rotor UAV, while the UAV serves as a separable long-range vision system for the UGV, providing top-down views of its environment, which are stitched and transformed into maps, and which are utilized towards the navigation of the robot hybrid. Multiple avenues of extension of our system and the concept are also introduced, illustrating the power of the separable-body heterogeneous symbiotic multi-robot system concept.
Keywords- UAV, UGV, hybrid robot, pilot-scale

I. INTRODUCTION

Unmanned Aerial Vehicles are limited by strong constraints regarding their capability of carrying large loads in relation to their size. Furthermore, their flight time and range limitations are also subject to such constraints, even more so for the case of VTOL aircraft which require large amounts of energy even for hovering to a point. Such limitations are also one of the main reasons that engineers often under-instrument UAVs, without being able to include in their payload heavy or energy-hungry sensor, actuator, communication or processing sub-systems, given weight and energy constraints. However, UAVs still have a lot of advantages in comparison to mobile robots: they have the capability of a large 3-D workspace which usually has much fewer obstacles, can often have much higher instantaneous velocities as compared to ground vehicles. Most importantly, they can observe a much larger area through their sensors given: their attitude which is much higher, the much fewer occlusions that they are subject to, and their enhanced ability to reach through flying positions and viewpoints where occlusions are further minimized.

On the other hand, mobile robots have numerous advantages too: they can carry a much larger load than comparable UAVs, and thus they can carry much larger power sources, as well as heavier or more power-hungry sensing, actuation, and processing subsystems. However, given that they have to stay in contact with the ground, they are much more susceptible to obstacles, harsh terrain, as well as occlusions and other sensing limitations.

The combination of these two types of robots, though, and their conceptualization as a unitary heterogeneous hybrid symbiotic system with on-the-fly separable and recombinable body parts, can create highly beneficial synergies: for example, sensing can become distributed, with top and advance-longer-range views coming from the UAV, while the power needs of the UAV as well transport and a safe docking and hiding area can be provided by the ground vehicle. Thus, the combined unitary hybrid can do much more as compared to the sum of the abilities of its parts. Numerous examples of application areas of such hybrid robots exist – autonomous observation and fire-fighting of forest areas; safe navigation and early hostility detection for mobile robots which are situated in an unknown environment, even for space applications. Of course, aircraft carriers are a good example of a widely-deployed manned analogue of such hybrids.

In this paper, we will present an example pilot-scale system, which was developed and tested indoors in our lab. This indoor autonomous hybrid system consists of smaller-size-and-power system as compared to a full-scale outdoor implementation; however, it has several advantages when it comes to research and development. First of all, cost: algorithms which can be transferred with only a few parameter adjustments to full-scale systems can be developed cheaply, without the need for expensive hardware. Second, minimization of test-time damages due to free fall from high attitudes; and third, the possibility to utilize precise indoor localization systems as well as other such equipment, which could not be utilized during development time outdoors. Thus, we believe that such small-scale pilots are highly valuable in order to catalyze accelerated research that can later be transferred to full-scale outdoor systems.

In this paper, we will start by presenting relevant existing work, then we will talk about the methods used and the results obtained, and provide a discussion, and finally, we will conclude the paper, after having introduced the multiple potential avenues for extension of the system and concept.

II. Related Work

In the past, related research has taken place in the area of multi-agent system such as UAV-UGV cooperation [1][2][3] and multi-robots[4][5] like multi-UAVs[6][7] and multi-UGVs[8][9][10]. UAVs and UGVs have several advantages and disadvantages over each other in terms of mobility, payload and perception abilities and past work[2][3] focuses on combining UAVs' and UGVs' advantages together to create a multi-robot system that can be implemented to do a specific task as in [1][2][7]. There have been many approaches for mapping and exploration of unknown environment with multi-robot system [4][5][9][11] which consists of several UAVs or UGVs, or both together as a system. Research in multi-robot system has been done as it has many advantages and application in many fields such as military, surveillance, etc. In [7], a team of UAVs are utilized for cooperative forest fire surveillance. Different types of vehicles can also be grouped together where UAVs and UGVs can work simultaneously to achieve a specific goal such as exploring unknown area and creating map of the explored area. Studies have been done not only on the application of the multi-robot system but also in how to optimize the decision making for exploration of the area [11] and path-planning [9] for the mobile robots. When multiple robots are present and to be controlled simultaneously, the system requires careful attention on how each robot behaves in order to avoid any collision or any unexpected scene [11]. Similar to our research, considerable research has been done in mapping and exploration of unknown environments [4][5][9][11]. But past work tend to use one type of mobile robots, either UAV [6][7][9] or UGV[3][10] to fullfill the task. Also it focuses on outdoor activities using different sensors such as GPS, stereo-vision cameras. In our work we combine a UAV with a UGV that explores and maps the unknown indoor environment using motion capture to obtain the location of the UAV and a camera installed on the UAV to take aerial photos. There has been a similar work of indoor environment mapping [8] using UGVs and sick laser. In our work, UAV provides clear aerial photos of the unknown environment and the main system installed on UGV creates a map of the explored area by the UAV then does the path-planning to move optimally from one point to another on the map.

III. Methods and Results

The purpose of the prototype system that was designed and implemented is to carry out a mission of finding an optimal navigation path for a mobile robot in an indoor environment, starting from a fixed initial point and going towards a desired target point, in minimum possible time. In the original experiment, in order not to be obstructed with localization which is not the focus of our attention, we worked on the assumption that we can localize both the mobile robot as well as the UAV in terms of position and pose, which were obtained through a vicon motion capture system. Our system though had no prior information regarding its local environment and the obstacles around it, and no sensors on the mobile robot were used towards that purpose. In order to achieve our purpose, we utilized a number of hardware and software modules, which we will describe below, as can be seen in the system architecture in Fig. 1.

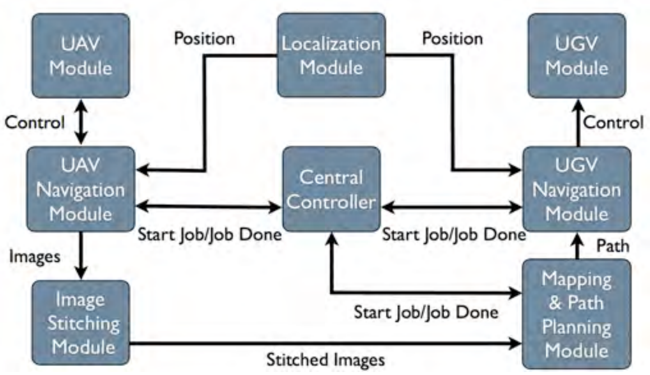


Fig. 1. Modular system architecture.

A. Unmanned Ground Vehicle (UGV)

The ground vehicle that was utilized is the Mobile Robots Pioneer P3-DX, which is equipped with two active wheels of constant direction placed in the front part of the robot, and one passive wheel which is freely rotating depending on the movement of the robot. This vehicle has the capability of moving towards the front or back, and to rotate clockwise or anticlockwise or to perform a combination of the above motions. Given our computational needs, the robot was equipped with a laptop computer, which was performing the task of controlling the system, through the software that we created. The motion of the UGV took place through the ARIA software library, through C++ code, by exercising external commands arriving through UDP sockets, and which are translated to special commands sent via a serial to the robot's onboard microcontroller, which directly controls the motors of the robot.

B. Localization Module

In order to know the position and pose of both the UAV and UGV, we utilized a vicon motion capture systsm which is comprised of six cameras placed perimetrically on the walls of room where our experiments took place. Special custom software is running on a dedicated PC which outputs a 2KHz timeseries of high-precision 1mm accuracy measurements of optical marker positions, that in our case were placed on the UAV and UGV in order for us to calculate in real time their position and pose. The output is sent out over Sockets using the UDP protocol.

C. Unmanned Aerial Vehicle (UAV)

The flying part of the system is comprised by a budget-cost quadrotor VTOL, namely the ARDrone by the Parrot company, which can move within 3D space using a proprietary stabilization and control algorithm in firmware. It is equipped with two color cameras of 240x320 pixels resolution, and sonar sensors for measuring attitude. Its onboard wireless communications system uses Wifi (802.11) through which UDP packets bidirectionally to communicate with the client controller application. The commands sent to the UAV in our case include setting desired Roll and Pitch angles, desired Yaw rotation speed, and desired attitude descent –ascent rate. The output of the system is the change of the rotation speed for every rotor, so that the above desired values can be sustained.

D. UAV Navigation Module

The UAV navigation and data collection algorithm was implanted in the LabView environment. This application controls the Pitch, Roll, Yaw, and Attitude of the UAV, and receives telemetry as well as video from the UAV in real time. Upon initial execution, the algorithm is in an idle state, waiting to receive the "Job Start" command from the central controller module. When it received this command, it starts the data collection process from the localization subsystem and from the UAV and then launches the UAV from the mobile robot on which it was landed. After having stabilized the flight altitude, it starts the navigation of the UAV, moving for the purposes of our experiment between 21 predefined setpoints above the unknown environment where the hybrid system resides. These points were selected in order to provide a sampling grid, and are dependent on the camera view angle, the flight altitude, the flight time and other such chracateristics. The density and number of points was also selected on the basis of the performance of the stitching algorithm, and the resulting navigation performance of the maps that are generated through the resulting stitched images. The controllers that were used are minimizing position, direction, and altitude errors, are of PID type, and were tuned using the Ziegler-Nichols method. If the UAV is within an accuracy radius of 1.5cm then it remains there for approximately 5 second, in order to be further stabilized and so that the camera views the ground from a parallel plane. If these conditions are reached, then the camera image is transmitted. After all 21 points have been reached and images acquired, the UAV is driven to landing mode, and after a successful landing, the "Job Done" signal is sent to the central controller, and the algorithm returns to idle mode.

E. Image Stitching (Mapping)

In this project, one of the most important tasks was to be able to create a clear map of the explored area using aerial photos taken from the UAV. This map is then processed for path-planning for the UGV. In order to create a map of the unknown environment, it requires sufficient number of photos of the area so that different images can be stitched together to create a bigger image of the explored area. In order to do the stitching task, a programming language called MATLAB is used with computer vision and image processing tool boxes.

To stitch images, Scale-invariant feature transform algorithm[12] which is also known as SIFT has been used which is one of the most widely used algorithm in computer vision to detect and extract key points in images. First, two images which overlap each other are taken and SIFT algorithm is applied on each image to extract key points in the images. After extracting key points from each image, Random Sample Consensus[13], also known as RANSAC algorithm is used in order to remove outliers of the key points found on each image and then solve the correspondence problem. RANSAC is used to find homography between the two images using a set of corresponding points. When the corresponding points and homography are known, two overlapping images can be stitched together by aligning two images and stitching the overlapping parts of the images.

F. Path-Planning and Navigation of UGV

a) Fast Marching and Path Planning

The Fast Marching method is a level set method, proposed by Osher and Sethian [14], [15] to solve the Eikonal equation:

$$1 = F(x)\left|\nabla T(x)\right| \quad (1)$$

which describes the motion of a front wave propagating in a non-homogeneous media where the speed F does not have to be the same everywhere, but it is always non-negative. T(x) is called the arrival function which computes the time the wave will take to reach a point x. The T(x) function is originated by a wave that grows from one single point (global minimum) at the source. As $F > 0$ the wave only grows, and hence, points farther from the source have greater T. A local minimum would involve that a point has a lesser T value than a neighbour point which is closer to the source, which is impossible, as this neighbour must have been reached by the wave before.

b) Application to Path Planning

The front wave expansion speed F can be directly assigned from the values of the environment modeled in a gridmap, where for each cell 0 means obstacles and collision-free space is labeled as 1. To obtain a path from a point p to a point q a wave is expanded from q until it reaches p. Due to wave expansion properties, the wavefront will follow the shortest time path between p and q. Even more, considering the propagation speed as constant, the trajectory will also be the shortest in terms of distance. The consequence is that the T function will be local-minima-free, with one global minimum at the goal point. Applying gradient descent over the T function from the goal point, the initial point will be reached. Fast Marching ensures that the path obtained is unique and complete.

Fig. 2 shows the result of applying FM to find a trajectory. The calculated path, although it is the shortest in length, runs too close to obstacles so it might not be a safe path. This causes the robot to go slowly when it is close to obstacles in order to avoid collisions. Therefore the path might also not be the shortest in time. In the following paragraphs we are introducing two other different methods based on Fast Marching which solve this problem: Fast Marching over the Voronoi Diagram and Fast Marching Square (FM2).

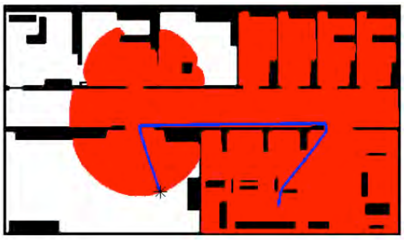


Fig. 2. Binary map and the path obtained using Fast Marching. The front wave is also drawn (red).

c) FM2 Path Planning Method

In the previous subsection, there was just one wave source at the target point. Here, all the obstacles are a source of the wave, and hence, several waves are being expanded at the same time [16]. As pixels get far from the obstacles, the computed T value is greater. This generates a new map that can be seen as a slowness map. If we consider the T value as a proportional measure to the maximum allowed speed of the robot at each point, we can appreciate that speeds are lower when a pixel is close to obstacles, and greater far from them. In fact, a robot whose speed at each point is given by the T value will never collide, as T→ 0 when approaching to the obstacles. Now, if we expand a wave from one point of the gridmap, considering that the expansion speed F(x; y) = T(x; y), being F(x; y) the speed at point x; y and T(x; y) the value of the slowness map at x; y, we will have that the expansion speed depends on the position. As the slowness map provides the maximum safe speed of the robot, the obtained trajectory is the fastest path (in time) assuming the robot moves at the maximum allowed speed at every point. Fig. 3 shows the performance of this algorithm.

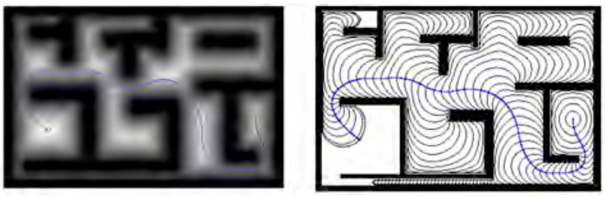


Fig. 3. Left - Slowness map and the path obtained with FM2 Right - Wavefronts at each iteration. The path is perpendicular to each front wave.

d) Integration of Fast Marching Square in the UAV-UGV Cooperation

As detailed in the previous section, the FM2 algorithm is based on a grid map representation of the environment. Therefore, the processing of the stitched images obtained in Section <write number> is focused on creating a binary map in which the obstacles will be represented with black (value 0) and the free space, in which the UGV is able to navigate, will be white (value 1).

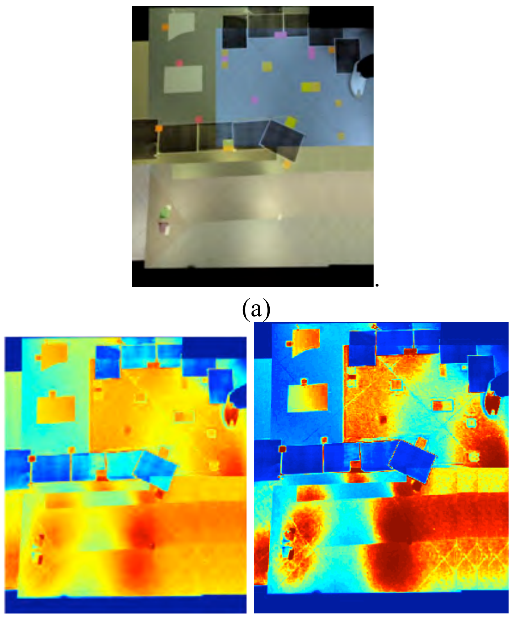
For this purpose, simple computer vision algorithms are employed. The steps described following are highly dependent on the application, the kind and size of UGV and also the type of environment (city, forest, desert, etc). Assuming that the obstacles in the environment use to be of a very different color of the walkable ground, the algorithm used to find out the occupancy map is the following:

The HSV histograms of the image are equalized in order to ease the following steps. Ground segmentation based on HSV color space values. All those objects which have a hue value within a specific range are labeled as obstacles.

A binary image is created in which the obstacles have value 1 (white) and the rest of the pixels have value 0 (black). Since this segmentation is likely to detect very small parts of the image as obstacles (due to noise), a closing of the image is necessary. This consists on an erosion of the image due to remove the small objects of the image followed by a dilation, which restores the size of the large obstacles. The size of the structuring element for the closing depends on the cell size employed the elevation of the UAV while obtaining the map, and so on. Finally, to be able to use this map for the path planning algorithm, the value for each pixel is inverted (Fig. 4).

We acknowledge that the obstacle detection algorithm can be improved in order to detect better the obstacles without hardcoding the range of the hue values, field in which there is a lot of literature. However, this is not the main objective of the paper, but the collaboration between UAV and UGV.

The goal point is labeled with a color label in the real scenario and the image is cut in order to have this goal point close to the (0,0) coordinates of the image. Using as initial point the current coordinates of the UGV, the FM2 algorithm is employed. An example of the path obtained is shown in the Fig.5.



(a)

(b) (c)

(d) (e)

Fig. 4. Algorithm results. a) Initial stitched image. b) Value (third dimension) of the initial map. In this case is the best parameter to use in the segmentation. c) Value equalized. d) Value equalized binarized. e) Same as d) after the closing operation and with the goal point in the (1,1) coordinates of the image.

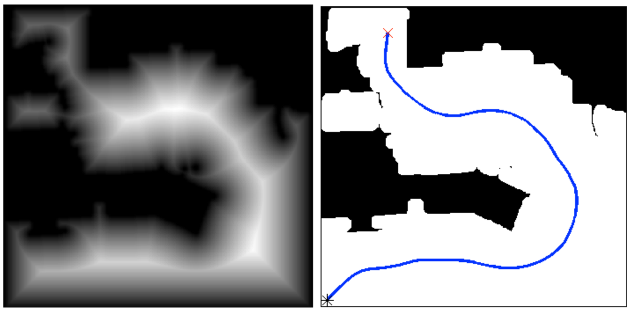


Fig. 5. Left – Velocities map obtained from the computer vision algorithm. Right - FM2 path obtained using the top point as an initial point and the bottom left corner as a goal point.

IV. Discussion of Future Steps

There exist multiple avenues for extension of our system and concept. First, one could extend the separable-body unitary hybrid robots to include more than two robots, and also many types of robots apart from UAVs and UGVs. An interesting stream of research is taking place towards this direction worldwide. Second, in the case of our system, we plan to further extend our quantitative evaluations of performance, and go through a further cycle of refinements and augmentations. Finally, we plan to investigate the porting of the system to a full-scale outdoors implementation, and comment on the actual issues that arise during such an attempt, in order to provide a number of guidelines for this process, that could be potentially usable in other systems too.

V. Conclusion

Motivated by the numerous potential synergies that exist, in this paper we have considered the conceptualization of a combination of a UGV with a UAV as a unitary separable-body hybrid heterogeneous system. After discussing the numerous advantages of an intermediate pilot-scale system before an actual full-scale implementation, we presented a pilot-scale prototype. In our system, a mobile robot UGV serves as a transport as well as recharge station for a lightweight quad-rotor UAV, while the UAV serves as a separable long-range vision system for the UGV, providing top-down views of its environment, which are stitched and transformed into maps, and which are utilized towards the navigation of the robot hybrid. We presented in detail our novel path planning and navigation method, as well as numerous quantitative and graphical results. Multiple avenues of extension of our system and the concept were also introduced, illustrating the power of the separable-body heterogeneous symbiotic multi-robot system concept.

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