A Low-Power, Compute Efficient Distributed Autonomous Multi-Robot System for Unknown Area Exploration

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***Abstract*— Recently, there has been an increasing realization that multi-robot systems can play a crucial role in providing solutions that will replace single robot systems due to efficiency/cost/scalability considerations. However, there are multiple practical challenges that need to be addressed to realize such systems. In this work, we develop a generic low power, compute efficient hardware platform to accomplish complex tasks using a team of robots. This platform is used to demonstrate unknown area exploration mission using a team of four robots. Further, practical challenges in deploying such multi-agent systems are discussed and the overall runtime analysis for the demo application is presented.**

I. Introduction

The concept of distributed, autonomous robotic system has gained increased attention and has brought tremendous changes in various socio-economic aspects of human society [1]. Mobile autonomous robotic systems have wide range of applications due to their ability to work in challenging unknown and unstructured environments without human intervention [2-3]. The collective (team) behavior emerges from the interaction between the robots and the interaction of the robots with the environment. There is a body of work that describes different algorithms and software capabilities to enable such teams of robots [4]. However, there is limited work on the practical aspects of realizing such systems of robots operating in a team capable of working autonomously in an unknown environment to accomplish challenging missions. To this end, we build a generic, capable robot system that can be used to enable variety of use cases where multi-agents collaboration is relevant. In this work, unknown area exploration is demonstrated using the developed system and different practical challenges are discussed.

The remainder of the paper is organized as below. The system architecture details are provided in Section II. Experimental setup is described in Section III. Results and practical challenges are discussed in Section IV and Section V, respectively. Conclusions are presented in Section VI.

II. System Architecture

The system design aspects for multi-robot collaboration in an unknown environment towards accomplishing the area coverage mission is presented in this section. 2D (terrestrial robots) are considered in this work. Note that, all the robots/agents in the system need not necessarily interact directly. Depending on the mission, size of the team, location of the agents in the team, and based on the optimization targeted, only a subset of robots can interact and still accomplish the overall mission. System architecture for the proposed approach is presented in Fig. 1.

Environment perception is a fundamental function that refers to the ability of a system to collect information and extract relevant knowledge from the environment. Perception provides the robot with crucial information on the navigation environment, surrounding location of obstacles, velocities, and even predictions of their future states. Based on the sensors incorporated, the environment perception task can be tackled by using infrared (IR), light detection and ranging (LiDAR), cameras, or a fusion between these devices. Depending on the available power and cost, the required sensor can be chosen. In the proposed system, generic interfaces are exposed for hooking up different sensors based on applications.

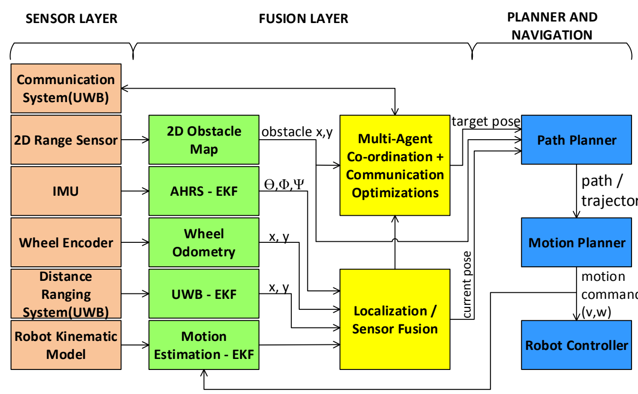

Fig. 1. System diagram of the proposed approach

Localization corresponds to the ability of the robot to determine its position (and heading) with respect to the environment. Accurate localization is a key parameter that allows information gathered by sensors to be tied to their physical location in a mobile robotic system. However, it is often very challenging due to unavailability of GPS (indoor environment), inaccuracies encountered with limited sensor capabilities and in general due to unknown environment. In this work, the fusion of inertial measurement unit (IMU), wheel odometry, distance ranging (using wireless radio) data is used for localizing a robot.

Multi-agent mission planning (coverage in this case) is an important high level module that runs on each robot. This algorithm uses the available information on individual robot to come up with the next move for the corresponding robot. In this work, compute efficient grid-based approach is used for exploring the unknown area. Based on the local sensor information, each robot maps the unknown area incrementally. Based on the location of the robot (if the robot goes out of a specific range), communication is triggered. At this point, the robots exchange required information with each other and update their knowledge on global coverage. Finally, once all the grids in the unknown area are marked/mapped - the mission is declared complete.

Planning refers to the process of providing path for the robot (through intermediate points) to move from the current location to the target location, while avoiding obstacles and optimizing over designed heuristics. A rapidly exploring random tree (RRT) [5] based local planner approach is used in this work to provide robot the required path. Controller portion refers to the ability of the robot to execute the planned motion. A motion control block is devised for the robot to physically move from current location to target location.

III. Experimental Setup

In this section, the research platform developed for multi robot collaboration is presented. The example mission is area coverage. In Fig.2, the details of compute and sensors used on this platform are described.

`Research platform`: To realize the algorithms and to demonstrate the utility of a team of robots, a robotic research platform was developed using off-the-shelf components. Being a research platform, the system was designed to cater to a more generic operation rather than application specific optimizations. The system needs to be flexible enough to add or update features, low cost to the end that it can be reproduced in large numbers and low power to enable enhanced runtime to suit targeted applications. Finally, the system should facilitate validation of the algorithms and findings. The complete experimental setup involved 4 identical robots (homogeneous) working together, but each robot singularly capable of handling the entire compute tasks (autonomous). Below are the major components on the platform.

`Compute sub-system`: The compute involved is handled by Intel Edison, a compute module from Intel, housing an Intel Atom CPU core [6] clocked at 500 MHz and a 32-bit Intel Quark micro-controller clocked at 100 MHz. It also includes 1GB of RAM integrated on the package along with a 4GB eMMC flash and other peripheral controllers (Wi-Fi, Bluetooth 4.0, USB, I2C, SPI, and UART). Note that, Edison based set up is much lower in power and lighter in compute compared to Intel's core based processors. All the sensors are interfaced directly to Intel Edison compute board.

`Sensor sub-system`: Below are the sensors used in this system. Note that, interfaces are provided for inclusion of other sensors based on application and requirement.

Ultra wide band (UWB) transceiver for communication and ranging: We use the Decawave DW1000 UWB chip as the radio transceiver for both data communication and distance ranging. It uses the IEEE 802.15.4-2011 UWB protocol [7]. The DW1000 offers good flexibility in terms of multiple channels, multiple data rates and packet sizes [8]. This lets us optimize the operations based on the current requirement (communication or ranging). It also comes with direct support for 2-way ranging and TDOA. The DW1000 uses a serial (SPI) interface to interact with the compute platform.

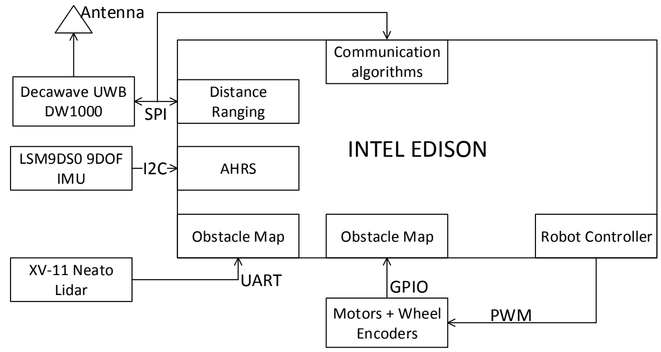

Fig. 2. Research platform with compute and sensor details

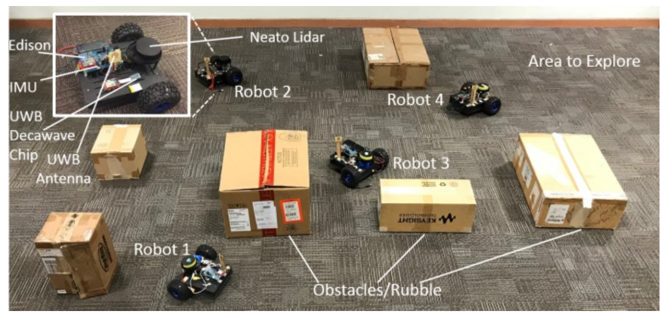

Fig. 3. A team of 4 robots working in unknown environment

IMU: The LSM9DS0 9DOF IMU from STMicroelectronics was selected to generate the 3D heading and angular velocity information [9]. It features three (3) acceleration, angular rate and magnetic field channels. The 16-bit output provides sufficient resolution to reach the accuracy required for our operation. We use an I2C interface to enable interaction between the IMU and the Intel Edison.

2D obstacle sensors: Selecting the right 2D obstacle sensor was one of the primary challenges involved in this development process. Considering the optimal requirement of an IR range sensor accompanied with a motor to scan a 2D region around the robot, a low cost and accurate IR obstacle sensor system is hard to come by in the present market. The XV-11 Neato LiDAR was selected for its comparatively lower cost and sufficiently reliable operation [10]. It uses UART to interact with the Intel Edison. A custom solution involving an individual IR sensor and a motor is expected to replace it in future versions of the platform.

IV. Results

The setup described in the previous section is used to test different algorithms for multi-robot collaboration. Individual experiments are carried out first to understand the practical implications. A team of 4 robots is then deployed to cover an unknown area. The compute (including localization, planner, coordination and navigation) was carried out on Intel ATOM core and mechanical structure was built using 3rd part chassis. The representative team of robots 4 robots is as shown in Fig.3. Finally, the overall runtime of the system is analyzed for distributed, autonomous coverage mission.

First, experiments are carried out to locate the position of the robot in an unknown indoor environment with different obstacles/rubble. With the described system ~15 cm localization accuracy is attained. Loop closure is achieved with the proposed system as shown in Fig. 4. Next, the unknown area coverage experiments were carried out. The deployed 4 robot team is provided with the boundary of the area to explore. The robots start from random start points and exchange location information for latest positions. A grid based coverage algorithm is employed for distributed coverage. With the team of 4 robots, an area of *5m x 5m* is covered in ~2mins. This includes the time required to exchanges information, take decisions and ultimately cover the area. Further, to test the autonomous behavior, two robots are suspended in the middle of the mission. The team of remaining two robots continued to explore the unknown area and the task was accomplished successfully. This demonstrates the distributed autonomous behavior of the overall system.

Finally, experiments are devised to determine the available system run times for unknown area coverage mission. With these experiments, we observed on each system that a 500mAh battery lasts for ~95mins operating all the algorithms. Same battery lasts for ~100mins for UWB based ranging/data sharing. The mechanical structure runs for ~90mins with 2100mAh battery. Various optimizations in algorithms and the actual chassis/mechanical form-factor are possible to further extend the operation time.

V. Key Challenges

Listed here are some of the key challenges observed in developing a system for multi-robot collaboration:

(i) First and the foremost is selecting the right platform and components. The compute platform should be closest to the target system, however, needs to be flexible and support active development and testing for different algorithms.

(ii) Right interfaces need to be enabled for testing and utilizing multiple sensors based on applications.

(iii) The radio needs to support both ranging and communication. Most of the radios (other than UWB/ZigBee) cannot give cms of ranging accuracy today.

(iv) IMU, 2D obstacle sensors need to match requirements in terms of frames-per-second and accuracy (based on the application).

(v) Enabling a system for optimizing no. of communication instances and the data transferred in each instance is critical.

(vi) Achieving co-ordination/time synchronization between the ranging packet transfers is a challenging task.

(vii) Non-line-of-sight condition detection and mitigation capabilities need to be enabled on the system.

(viii) Scalability in the number of robots in a team is a critical aspect – especially in a large unknown area.

(viii) Localization accuracy in a GPS denied environment could pose serious inaccuracies breaking the overall system

(ix) Providing the required debug interfaces to test the multi-robot operation is a key challenge on the system.

(x) In general, achieving reliable operations using obstacle data on a moving robot system with a need to balance the compute complexity and accuracy for extended operation time is a major challenge.

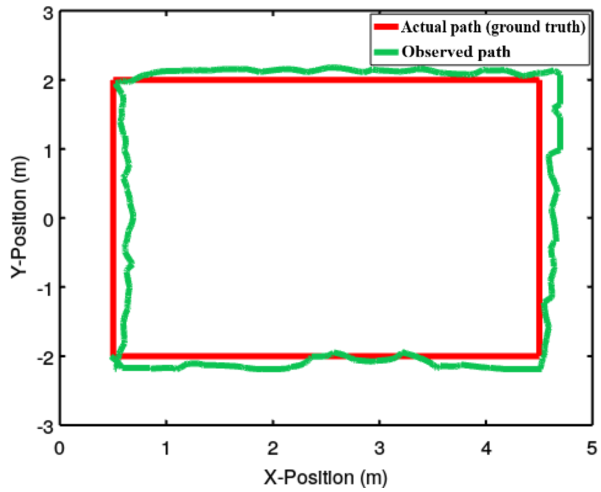

Fig. 4. Localization loop closure with the proposed system

VI. Conclusion

Building robotic systems to operate in unknown and unstructured environments is a challenging frontier for robotics research. Such systems must operate for extended periods of time in complex domains to accomplish a given mission. This requires various system level issues to be addressed. In this work, a generic robotic platform with appropriate compute and sensing capabilities is developed. This system is used in a 4-robot team set up to demonstrate distributed autonomous unknown area coverage task. Various challenges in enabling such systems are discussed. Further, the system developed in this work can be used to devise and test different optimization algorithms for coverage, search, tracking, and path planning for energy efficient and robust operation.

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