Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Autonomous Power Distribution System

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Abstract: This paper describes path planning and control of an autonomous power distribution system. The aim is to study the use of the autonomous mobile power-grid systems after disasters to accelerate search, rescue, and recovery efforts. The concept is demonstrated through an autonomous electrical cabling and connection mission between a power source and a power load in a cluttered environment using lab-size platforms. The developed system will be scalable to real-size. The ultimate goal of this work is developing intelligent power electronics and a distributed autonomous mobile microgrid. It will be capable of regulating power flow at a desired voltage and frequency level, meeting load demands and adaptable to changes in situation, power demands, or generations.

1. INTRODUCTION

Recent search-and-rescue efforts following Colorado's floods brought back the memory of Hurricane Katrina's aftermath in 2005 and the importance of a prepared emergency-response system to work quickly and effectively in order to improve the chance of helping victims. Depending on the size and type of the disaster, the rescue operations are conducted from the air, ground, or even water; many times in parallel. In some cases, due to intensity of the disaster, the rescue efforts are complicated and require inter-agency rescue teams. A large-scale disaster relief operation requires: coordination of many teams of first responders, capability to assess the situation, brisk adaptation to changes in the environment, and ability to rapidly reorganize the teams.

These many factors emphasize the importance of the communication between rescue teams, rescue management, and area residents. In such incidents, any means of long-distance communication becomes very critical. Cellular phones are one of the most common and available communication methods today. These devices can be extremely helpful by accelerating first response activities and also the victim's ability to inform their status and whereabouts. Unfortunately, in such circumstances cellular towers are often rendered silent due to electrical power shut off following the event of a disaster. Cellular towers often have backup generators, but these generators have limited energy capacity and are often damaged during a disaster Kwasinski et al. [2009]. In order to overcome power shortage, personnel will take additional generators to the site as soon as possible. However, this response is delayed in many cases due to initial concerns of protecting life and property. The bigger issue is that a great number of communication nodes are usually located in remote or hard to reach places. This makes it even more difficult to access in the event of a disaster. Even after distributing power to the system, personnel have to continuously refuel the generators to keep the system up and running.

An autonomous microgrid system that can be deployed and re-establish electrical power for the crucial components of the communication system with minimal human interference can have a significant impact in these situations. This system can be more effective and enable recovery of the communication system faster than traditional methods if it 1) contains sources to generate electrical power and 2) has a self-configurable framework to reach optimal formation based on power demand. Such a system can also reduce the fuel delivery demands.

The idea of having an autonomous mobile power-grid is a recent application of autonomous vehicles and currently in its initial stages of research Weaver et al. [2012]. However, teams of autonomous robots have been used to assist first responders in search and rescue. These mobile robots have also been instrumental in restoration of communication networks at various disaster sites by creating ad-hoc nodes and networks. Our ultimate goal is to integrate vehicle robotics, intelligent power electronics, and electric power assets creating self-organizing, ad-hoc electric microgrids. These components ensure capability to quickly restore power to a critical area. Our first aim is to find and validate practical solutions for control of a mobile power-grid.

In this work, we pursue the idea of using autonomous microgrid systems for re-powering communication nodes and study the required components for achieving this goal. These communication nodes are typically served by 208 V_{ac} three-phase power diesel backup generators. However, in the case where the generators may not be available, the autonomous microgrid robots can be dropped on sight. For this application the robots would be equipped with 208 V_{ac} three-phase power sources, line connections and power conversion components Sannino et al. [2003]. The general steps that the system will take are:

(1) Robot assets arrive and assess the power requirements of the local system.
(2) Robots autonomously physically connect sources and loads into a microgrid structure.
(3) The on-board power electronics convert source energy to a common distribution level.
(4) Load connected robots convert the distribution voltage to the needs of the load.
(5) Robots re-configure system as energy assets and load change.

This concept requires extensive coordination of many distinct research disciplines, including path planning and coordination of autonomous vehicles, power electronics and microgrids, and disaster impacts and response.

This paper describes electrical cabling and connection mission between one power source and one power load using a lab-size autonomous vehicle platform in a cluttered environment with static obstacles. While accomplishing this task, the aim was to develop an infrastructure that can easily serve as a base for a real-size system. This development is the first step towards having a team of autonomous robots with different functions that make the team capable of performing as a mobile microgrid to power up multiple power loads. The hardware used in this work is detailed in Section 2. Section 3 describes the path planning and control algorithm. Results are presented in Section 4. Future work is discussed in Section 5.

2. HARDWARE SPECIFICATIONS

The following explains the detail of the setup for this work which was used to satisfy the basic needs of having a functional and consistent autonomous robotic system.

2.1 Ground Robot

For prototyping the algorithms, a small mobile robot platform known as DaNI was used. DaNI is part of the National Instruments Robotics Starter Kit and is made specifically for teaching and research purposes.

The DaNI is equipped with the National Instruments sbRIO-09632. The sbRIO (Single-Board Reconfigurable Input/Output) is an embedded controller designed with real-time processing and rapid prototyping in mind. It features a field-programmable gate array (FPGA) and I/O ports that allow communication with various sensors.

The sbRIO allows network traffic by means of both web and file servers. If needed it can also support communication via RS-232 serial port. The 256MB on-board non volatile memory was utilized in order to: store and run the obstacle avoidance, path planning, and path tracking.

For the close area obstacle recognition and distance measurement a simple IR sensor was used. This particular IR sensor has a range between 20 and 150cm. This sensor was mounted on a servo motor allowing a data return range between -75° to 75° in front of the DaNI.

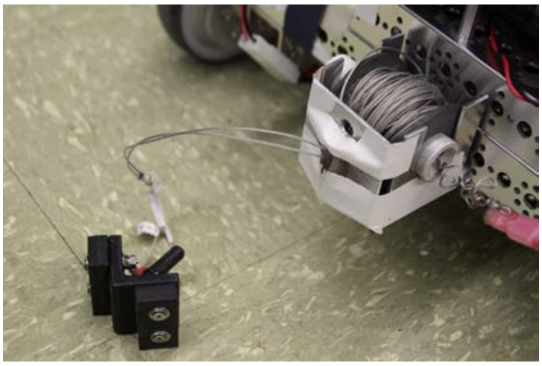

Fig. 1. Male magnetic connector with wire pulley

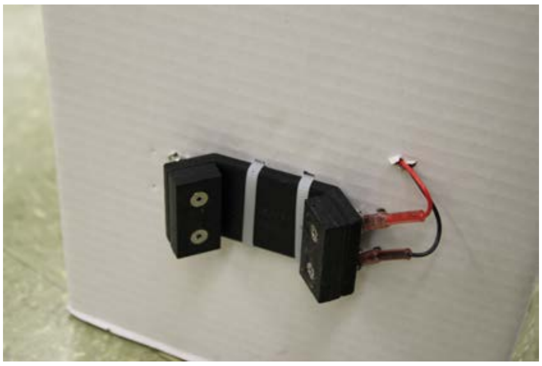

Fig. 2. Female magnetic connector

2.2 Power Source and Power Load Connections

The main task is accomplishing physical connection between an area known as a source and another classified as a load. Establishing a good electrical connection is a major factor, despite performing in cluttered unknown areas. In this project a magnetic connection was designed in order to reduce the risk of faulty connection. For this design, neodymium magnets with a protective coating was selected. The magnets have two countersunk holes which facilitate mounting electrical connections through the magnet while remaining shielded of the magnet. The polarization property of the magnets allow the electrical connectors to align properly for every connection. The angled design of magnet mounts also helps with eliminating the risk of misalignment. Each connection includes a male (Fig. 1) and a female part (Fig. 2). The male connectors are attached to the robot and female connectors are attached to power source or power load.

As the agent approaches the target, the male connector is absorbed by the female connector and pulls out of the mount on the agent and sticks to it. Two wires are connected to this male part that are rolled around a pulley (Fig. 1) and unwind as the agent moves away from the target. The other side of these wires go through the pulley and come out of the center of it and connect to another pulley with the same structure with another male connector.

2.3 Camera system

In order to accurately measure the position of the DaNI a Qualisys motion capture camera system is used. The

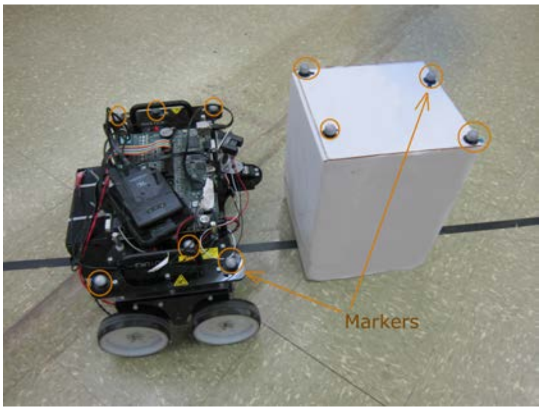

Fig. 3. Marker placement on robot and object

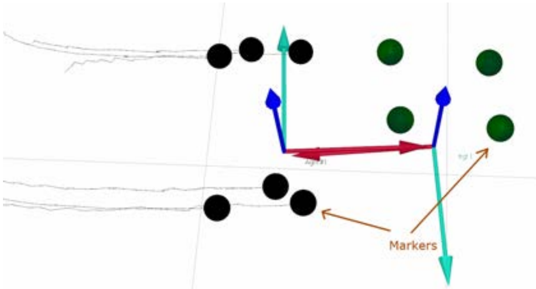

Fig. 4. 3D representation of objects in workspace by camera system software utilizing markers

camera system allows the detection and localization of objects. The cameras work by emitting light in the infrared (IR) spectrum and reflecting off of the IR markers (Fig. 3) within the area. These reflections are then recorded with a high frame rate. The camera software can track individual objects by means of the markers positioned on the actual object very accurately (Fig. 4).

Three hardware components mentioned above (subsections 2.1-2.3) are stepping stones for building an interactive system that is capable of performing autonomous power connection. In this system, the ground robot needs to be equipped with logical processes to accomplish the operation.

3. ALGORITHM

Our aim is to develop a motion planning algorithm that accounts for uncertainty in predictions; providing real-time guarantees on the performance of planning and reaching the targets while making a connection.

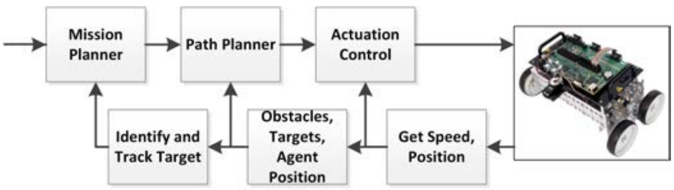

Fig. 5. Mission hierarchy with multi-timescale feedback

A multi-layered hierarchy has shown to be a practical method of administrating an autonomous mission Burgard et al. [1999],Quinlan and Khatib [1993]. In this project a mission control hierarchy with multi-feedback as illustrated in Fig. 5 has been developed. Each block carries out specific tasks (details described in 3.1-3.3) to provide on-site autonomous assessment, generate safe paths, and facilitate physical connection. The developed process is general enough for use in a real-size system that includes different perception modules and different sensor suites. As shown in Fig. 5, mission planner takes the task from the user and separates the mission to multiple sub-goals. The mission planner sends the first sub-goal to the path planner. Later during the mission and based on the information gathered from the robot and environment, this algorithm decides when and which sub-goal to switch while maintaining the quality of mission accomplishment. These sub-goals are fed to the path planner one at a time. This level of the algorithm decides on the future position and direction of the robot based on the sub-goal, current position of robot, and the visible obstacles. Actuation control achieves these states using a feedback controller and sends signals to hardware. Speed and position of the robot is fed back to actuation control in order to minimize the error in the robots behavior.

3.1 Mission Planner

This high level algorithm is developed to control the stages of accomplishing the power distribution mission.

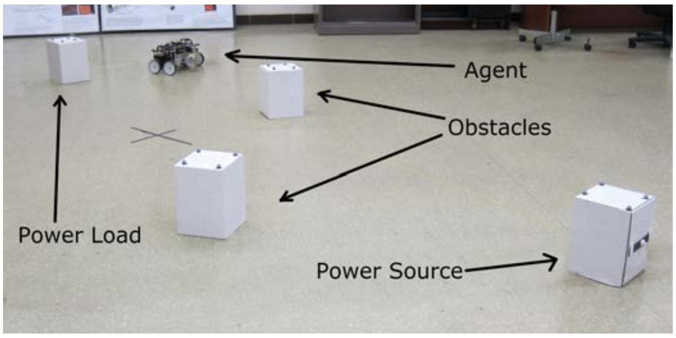

Fig. 6. Position of power source, power load, obstacles, and agent in the workspace

Fig. 6 shows a simple testbed for the power distribution mission. Mission planner decides on which target to be set as the destination at each moment through-out the mission. In order to make this decision at any moment, the mission planner needs information about position and orientation of the power source and the power load and the level of progress already made on the mission stages. These stages are: 1) moving to an imaginary target with specified distance in front of the power source connection point, 2) moving to the power source connection point, 3) departing from power source connection point, 4) moving to an imaginary target with specified distance in front of the power load connection point, and 5) moving to the power load connection point. The reason for having an imaginary target in front of the connection points is to ensure proper facing while making the electrical connection. After finishing each stage, the mission planner sends the target of the next stage to the path planner.

3.2 Path Planner

Path planning algorithm is illustrated in Fig. 7. This algorithm is based on the idea of gap finding and defining sub-goals for the robot in situations where it can not move directly towards its target. The sub-goal is chosen by studying the obstacle in front of the robot and choosing a sub-goal on one of the sides of the obstacle with enough clearance. The procedure consists of taking a straight path to reach a target point and facing the target. The agent starts following the straight line towards its target and runs the direction choosing algorithm at the same time. Whenever the direction choosing algorithm senses a difference between the target direction and a suggested direction that is more than a specified constant, it concludes that there is an obstacle in its path (refer to Fig. 9 for instance). At this time the distance from the obstacle is saved as a variable. The agent then starts moving in the suggested (alternative) direction only as far as the distance variable allows, avoiding collision. After reaching the end of the alternative line, agent faces the direction of actual target again and repeats the process until it reaches the destination.

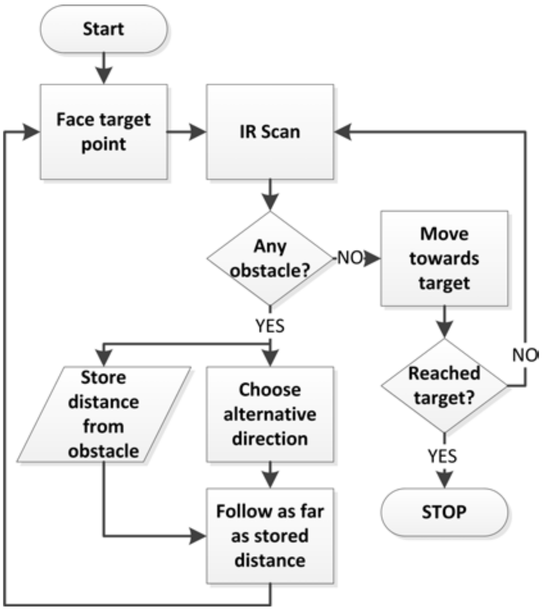

Fig. 7. Path planning and target reaching algorithm

An unknown workspace requires repeated execution of the path planning algorithm to facilitate robust avoidance from moving obstacles or late recognized obstacles. Moreover, the system should tolerate errors caused by the noises and disturbances in the environment.

3.3 Actuation Control

A feedback controller was designed using the first order kinematics model of the vehicle. The mathematical model of robot's kinematics can be described as follow Klancar et al. [2005]:

$$\begin{bmatrix}\dot{x}_c\\ \dot{y}_c\\ \dot{\theta}_c\end{bmatrix} = \begin{bmatrix}\cos(\theta) & 0\\ \sin(\theta) & 0\\ 0 & 1\end{bmatrix} . \begin{bmatrix}v\\ w\end{bmatrix}$$

where v and w are tangential and angular velocities of robot and x_c, y_c and θ_c are position and direction of vehicle in the workspace. A trajectory can be defined as a function of time like $(x_r(t), y_r(t))$ using the inverse kinematic equation and this trajectory can be translated to robot inputs for feed-forward control.

$$v_r(t) = \pm\sqrt{\dot{x}_r^2(t) + \dot{y}_r^2(t))}$$

$$w_r(t) = \frac{\dot{x}_r(t)\ddot{y}_r(t) - \dot{y}_r(t)\ddot{x}_r(t)}{x_r(t), y_r(t)}$$

This kind of mobile vehicle usually takes the wheel velocity as input which can be derived from feed-forward control inputs mentioned earlier, $v_R = v + \frac{wL}{2}$ and $v_L = v - \frac{wL}{2}$, where v_L is the velocity of left wheel and v_R is the velocity of right wheel.

Defining errors as differences between reference point on the path and robot's position is the first step in forming feedback controller Klancar et al. [2005].

$$\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix} = \begin{bmatrix}cos(\theta) & sin(\theta) & 0\\ -sin(\theta) & cos(\theta) & 0\\ 0 & 0 & 1\end{bmatrix} . \begin{bmatrix}x_r - x\\ y_r - y\\ \theta_r - \theta\end{bmatrix}$$

After linearizing around operating point ($e_1 = e_2 = e_3 = 0, v_1 = v_2 = 0$) feedback values can be calculated from

$$\begin{bmatrix}v_1\\ v_2\end{bmatrix} = \begin{bmatrix}-k_1 & 0 & 0\\ 0 & -sign(u_{r1})k_2 & -k_3\end{bmatrix} . \begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix}$$

A proportional feedback controller was used and the gains were tuned based on trail and error considering hardware limitations, algorithms and data transfer rates which can have great effects on stability of the robot.

A robot velocity controller algorithm was used during different stages of the mission to conservatively achieve touching the target (power source or load) and avoid the overshoot and correction process. This algorithm takes position of agent and target into account and determines the speed of the robot. The robot starts slowing down from commanded velocity when it gets close to the target and stops at the predefined distance.

This process ensures successful electrical connection with proper facing for making the connection.

3.4 Target, Agent, and Obstacle Monitoring

Knowledge of position and the state of targets, vehicle, and obstacles are important information needed for assuring a successful mission. This information is the input of hierarchy blocks and is updated during the whole operation as feedback to these blocks.

Position of targets and agents are obtained from the camera system. This approach of data gathering was used in order to imitate the GPS system. IR sensor was used to detect existence and placement of obstacles. IR sensor has been mounted on a servo which oscillates to the right and left in order to imitate scans of a two dimensional laser range finder.

As Fig. 8 shows each IR reading goes through a Butterworth filter in order to reduce noise. The filtered data then goes into the direction choosing algorithm. Based on this

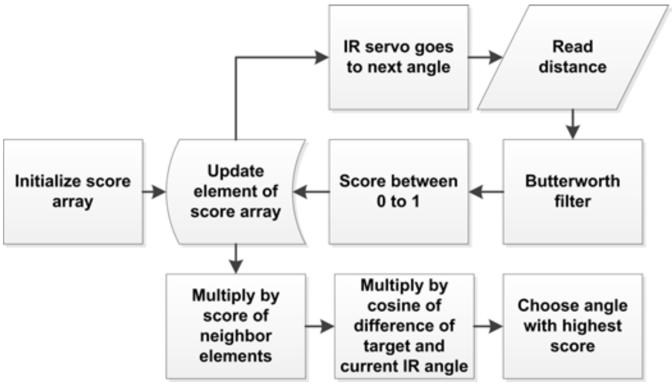

Fig. 8. Direction choosing algorithm using IR scan

algorithm each angle in the scanning area gets a score between zero and one. If the IR reading for an angle is less than a constant (e.g. 100 cm), it gets a score of zero and if it's more than a larger constant (e.g. 150 cm), it receives a score of 1. All the readings in between get scores based on linear interpolation. All these scores are put into an array that has an element to represent each angle. In the next step each score (element) is multiplied with its neighbors (e.g. 25 neighbors on each side) this allows the algorithm to choose a direction with neighbors of equally good scores. Then score of each angle is multiplied with cosine of angular difference with target's direction so that the algorithm has a tendency to choose a direction close to target's direction, but at the same time this direction has a reasonable distance from obstacle due to multiplication by its neighbors. The number of affecting neighbors is dependent on the accuracy and scanning rate of proximity sensor and geometrical properties of the robot. In this case accuracy and scanning rate had most of the effect on risk of crashing into obstacles, so the number of affecting neighbors was chosen based on trial and error only. A more reliable proximity sensor equipped with an algorithm which considers the geometric properties of robot can result in choosing directions that not only don't result in colliding with obstacles but eliminate the chance of choosing a direction too far from obstacle and lose time efficiency.

4. ALGORITHM RESULT

The algorithms discussed in Section 3 were validated in a lab-size setting using the hardware discussed in Section 2. Fig. 6 illustrtates a sample test setup which includes power source, power load, obstacles and agent. We will present the results from obstacle avoidance and cabling operation to confirm the functionality of the inner algorithms such as path planning, path tracking, and velocity control.

The Robot's paths during different stages of the mission are displayed in Fig. 10 and 11. These figures present the path of the agent in order to avoid collision with obstacles (red markers). It should be noted that no information regarding the position of obstacles was fed into the algorithm from the camera system and the markers on obstacles were used to just display their relative position.

Obstacle avoidance is accomplished using an IR sensor. Fig. 9 illustrates 1) a sample of IR sensor readings, 2) process results of these readings based on the algorithm,

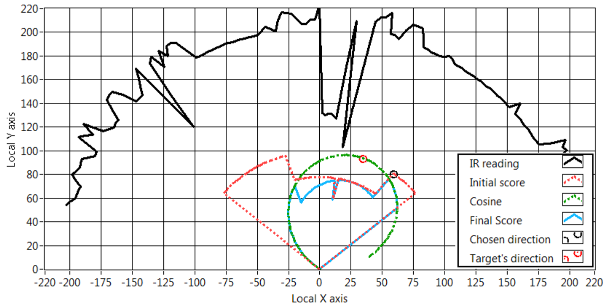

Fig. 9. Example of IR readings, scoring, and direction choosing results

and 3) the final output. The black line represents IR readings after going through a Butterworth filter. The red line shows the score of each angle multiplied by its neighbors. In order to have a better illustration of these scores, they are all multiplied by a factor of 100 before displaying them on the graph. The green line is the cosine value of the absolute of subtracting each angle from the desired angle (target's direction). The blue line is the multiplication of scores represented by the red line and cosine values. Finally the black circle shows the direction chosen for the vehicle (by algorithm) in order to avoid obstacles. It should be noted that the black circle has a conservative distance from obstacles observed.

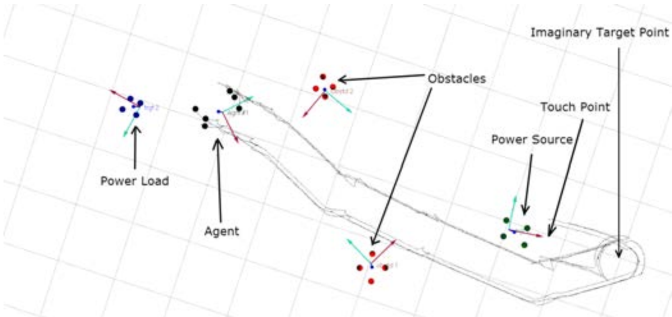

Fig. 10. Test results of agent avoiding obstacles and reaching the touch point of power source (agent is positioned at the start point)

Fig. 11. Test results of agent leaving the power source, avoiding obstacles, and reaching the power load (agent's final position)

Fig. 10 shows the path of the agent (black markers) from the start point to the imaginary target point and then to the touch point of the power source (green markers). Each power node in this scenario has a touch point. At the start of the code, the agent chooses a target point with a reasonable distance from the first target's touch point and moves towards it. The first target represents the power source. At the same time all the other codes such as IR and direction choosing are running, so in case the agent senses any obstacle while it's moving towards the imaginary target point, it will try to avoid it. After reaching the imaginary target point, the actual touch point is chosen as the destination so the agent starts moving towards the actual touch point. This process results in making the connection with proper facing. After a successful connection, the imaginary point is set as the destination again and a negative velocity is set for the agent. the result of this step is that the robot is moving backward, away from the touch point in order to avoid collision before continuing with its operation. Next, all these steps are repeated for the second target which represents the power load. Fig. 11 illustrates the path from the power source to the second imaginary target point and then to the power load (ark blue markers).

Another test setup with a large number of arbitrary obstacles with sufficient height for IR sensor was made in order to study the robustness of achieving magnetic connection and path planning algorithm. This setup is displayed in Fig. 12.

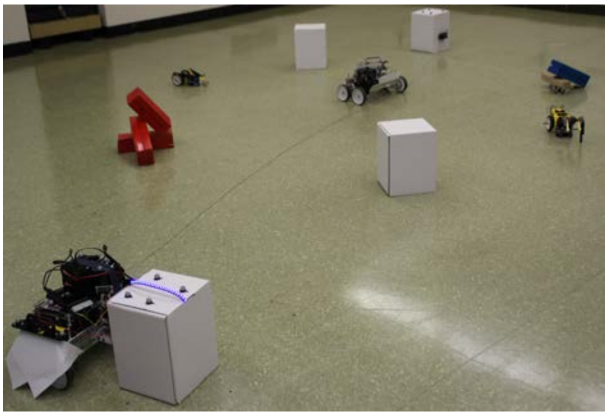

Fig. 12. Agent has autonomously connected the power source to the power load

5. CONCLUSION/ FUTURE WORK

In this paper, we presented proof of a concept stating that a self-configuring autonomous microgrid has great potential for both civilian and military disaster recovery operations. The focus is using autonomous mobile power-grids to help re-establish power. The organization, layout, and operation of such a mobile robotic microgrid are highly dependent on the assets in the area of operation. In this effort a lab-size hardware setup is used to demonstrate the physical connection and wiring of the microgrid by mobile robots. A practical path planning and control strategy is presented that accounts for uncertainty in predictions, provides efficient path planning, reaches the targets, and makes secure connections. The algorithm is scalable to real-size robots and different perception modules and sensor suites.

Future work will include the integration of autonomous mobile platforms and Power Electronic Building Block

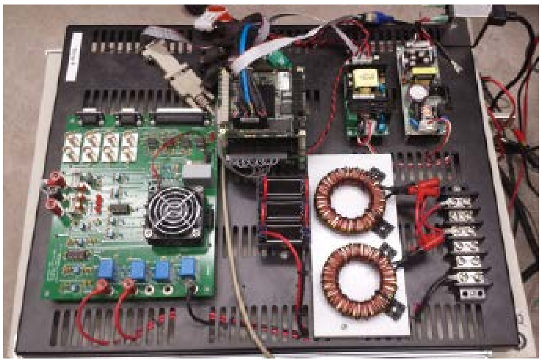

Fig. 13. Power Electronic Building Block (PEBB)

(PEBB) to create self-organizing, ad-hoc electric micro-grids. Michigan Tech's team has also designed and developed a PEBB module illustrated in Fig. 13. Each module is capable of power conversion of up to 1 kW. This hardware enables a very flexible and re-configurable platform to develop algorithms and controls for dc and ac microgrids. As this project progresses, the power electronics, power distribution , and physical connections are being developed in-house.

With this approach, the developed ad-hoc electric microgrid system is highly reconfigurable and robust. We believe that once the physical electrical system is connected, intelligent power electronics on the robots will automatically determine the required energy conversion to meet the energy and power consumption of the loads. If loads, generation, or other assets change, then the nodes can physically and electrically reconfigure to meet the new demand or generate new configurations to compensate for renewable energy generation fluctuations and energy storage.

REFERENCES

W. Burgard, A. B. Cremers, D. Fox, D. Hähnel, G. Lakemeyer, D. Schulz, W. Steiner, and S. Thrun. Experiences with an interactive museum tour-guide robot. *Artificial intelligence*, 114(1):3–55, 1999.

G. Klancar, D. Matko, and S. Blazic. Mobile robot control on a reference path. In *Proceedings of the 2005 IEEE International Symposium on Intelligent Control, 2005. Mediterrean Conference on Control and Automation*, pages 1343–1348. IEEE, 2005.

A. Kwasinski, W. W. Weaver, P. L. Chapman, and P. T. Krein. Telecommunications power plant damage assessment for hurricane katrina–site survey and follow-up results. *IEEE Systems Journal*, 3(3):277–287, 2009.

S. Quinlan and O. Khatib. Elastic bands: Connecting path planning and control. In *Robotics and Automation, 1993. Proceedings., 1993 IEEE International Conference on*, pages 802–807. IEEE, 1993.

A. Sannino, G. Postiglione, and M. H J Bollen. Feasibility of a dc network for commercial facilities. *IEEE Transactions on Industry Applications*, 39(5):1499–1507, 2003. ISSN 0093-9994. doi: 10.1109/TIA.2003.816517.

W. W. Weaver, N. Mahmoudian, and G. Parker. Autonomous mobile power blocks for prepositioned power conversion and distribution. In *TARDEC Ground Vehicle Systems Engineering and Technology Symposium*, 2012.