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AUTONOMOUS MOBILE POWER BLOCKS FOR PREPOSITIONED POWER CONVERSION AND DISTRIBUTION

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ABSTRACT

Situations exist that require the ability to preposition a basic level of energy infrastructure. Exploring and developing the arctic's oil potential, providing power to areas damaged by natural or man-made disasters, and deploying forward operating bases are some examples. This project will develop and create a proof-of-concept electric power prepositioning system using small autonomous swarm robots each containing a power electronic building block. Given a high-level power delivery requirement, the robots will self-organize and physically link with each other to connect power sources to storage and end loads. Each robot mobile agent will need to determine both its positioning and energy conversion strategy that will deliver energy generated at one voltage and frequency to an end load requiring a different voltage and frequency. Although small-scale robots will be used to develop the negotiation strategies, scalability to existing, large-scale robotic vehicles will be investigated to create prepositioned power grids in the 100 kW - 1 MW range. This concept will create a new capability for power grid deployment while increasing the state-of-the-art in multi-objective agent control.

INTRODUCTION

An electrical power network is comprised of devices that generate, consume, and store energy across a broad range of power levels. From large scale electric power grids and microgrids down to small scale electronics, they are typically deployed using a fixed-infrastructure architecture that cannot expand or contract without significant human intervention. Mobile, monolithic power systems exist, but are also not readily scalable to exploit surrounding power sources and storage devices. However, if a power network is constructed from physically independent and autonomous building blocks then it would be infinitely re-configurable and adaptable to changing needs.

In recent years there have been many research studies on microgrid distributed control and re-configurability [1, 7, 8]. These applications all focused on micorgrids whose electrical components maintained fixed physical positions and connections. Creating power networks using modular and physically autonomous subsystems provides enhanced adaptability, but it introduces technical challenges not addressed by previous research. The ability to reconfigure to achieve specified power requirements and to minimize other attributes such as fuel consumption, acoustic signature, thermal signature, etc. is an open research area of real-time, agent-level optimization and control.

Multi autonomous vehicles (multi robots) have been used as mobile sensor networks for surveillance and data collection for different purposes in air, ground, and water [2-6]. A key contribution of the concept presented in this paper is the integration of ground autonomous vehicles, intelligent power electronics and electric power assets to create self-organizing, ad-hoc microgrids. Three autonomous microgrid robots, each with different power network functionality, are shown in Figure 1. One has renewable energy generation and storage capability, another has a conventional diesel genset and the third contains intelligent power electronics for conversion and connection. After assessing the power requirements and available resources, they would physically organize and electrically interconnect themselves to form a microgrid. Once physically arraigned and electrically interconnected, the intelligent power electronics and distributed agent based control will regulate power flows at desired voltage and frequency levels to meet load demands.

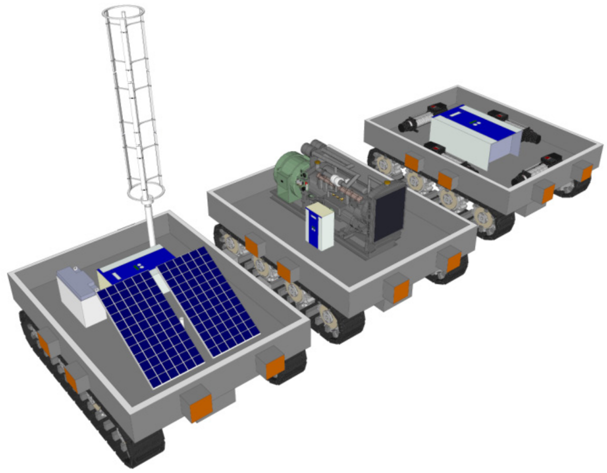


Figure 1: Concept models of autonomous microgrid robots. Left: renewable energy, middle: conventional genset, right: connection/conversion.

OPERATIONAL STEPS

The organization, layout and operation of such a mobile robotic microgrid are highly dependent on the assets in the area of operation. However, in general there will be energy sources and loads that may be fixed position or on a mobile robotic platform. All the assets must communicate over some channel which could include a wireless Ethernet network. The communications between mobile and stationary systems would establish a table of assets that will include power, voltage and relative locations.

The first step in operation is the physical connection and wiring of the microgrid by mobile converter robots. This will connect sources and loads electrically. Once the physical electrical system is connected there will be intelligent power electronics on the robots to do the required energy conversion to meet the energy and power needs of the loads.

The system shown in Figure 2 is a small conceptual example system that will be used to illustrate the concept of autonomous mobile microgrids. The system is comprised of two autonomous microgrid robots, a power converter robot and a power generation robot, a stationary power source node and a stationary power load node. The power source node is representative of a photovoltaic array, and the power load could be representative of a hybrid vehicle charging station.

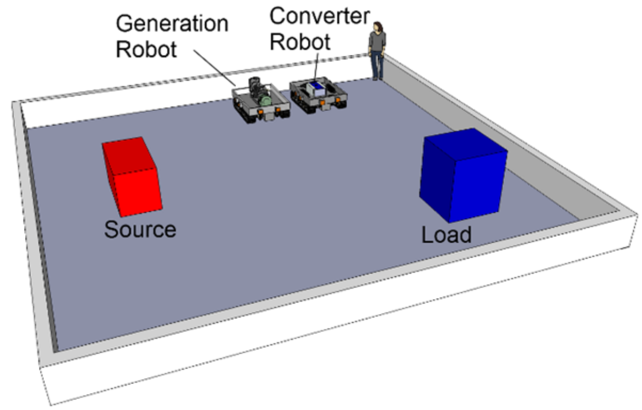


Figure 2: Illustrative example system with one converter robot, one generator robot, a source node (red) and a load node (blue).

ROBOTIC SYSTEM

The autonomous vehicle system employs a hybrid of planning and behavior based control architectures. The software structure can be divided into 1) perception, 2) localization, 3) cognition, and 4) motion control which are performed in multi-level timing sequence. The four components can be described as follows: perception consists of acquiring and processing sensor data such as sonar and vision system snapshots. Determining and updating the vehicle states is defined as localization process. The cognition process involves locating and validating targets and avoiding obstacles. The motion control component addresses how to reach targets and make connections. Figure 3 illustrates the system architecture block diagram utilizing a small laboratory hardware platform.

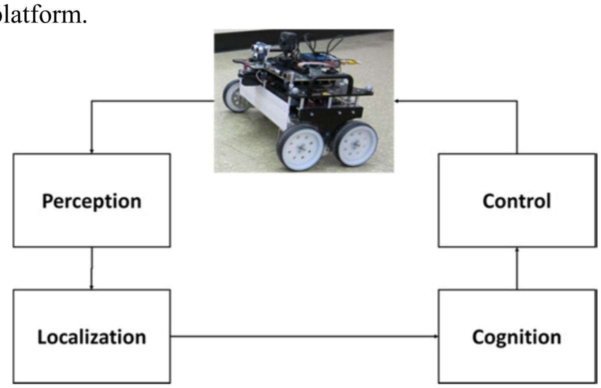


Figure 3: High level system architecture

A small laboratory hardware platform autonomous vehicle system will be used to illustrate the initial concept of connecting sources to loads. The system includes a lab-scale fully assembled robot, a sonar sensor, an analog video camera, and an analog frame grabber to capture still snapshots from the analog stream. The autonomous vehicle system software is programmed in LabVIEW and a multi-level programming approach is implemented. Multi-level programming allows different processing time for different components and integration of vision system into control system. Also, the perception modules require individually dedicated program levels. The main level consists of sonar reading and localization which happens every 10 ms, the next level is cognition and motion control which is performed every 20 ms, camera data reading occurs every 50 ms, and overhead computations are updated every 100 ms. Figure 4 shows the interaction of these modules through a flowchart while reaching targeted stationary power source nodes.

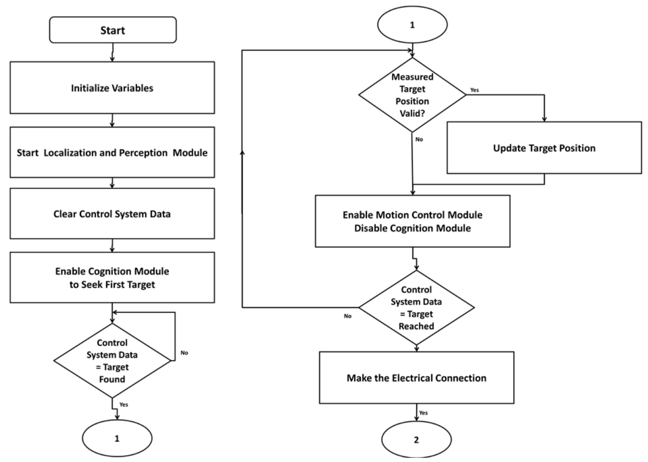
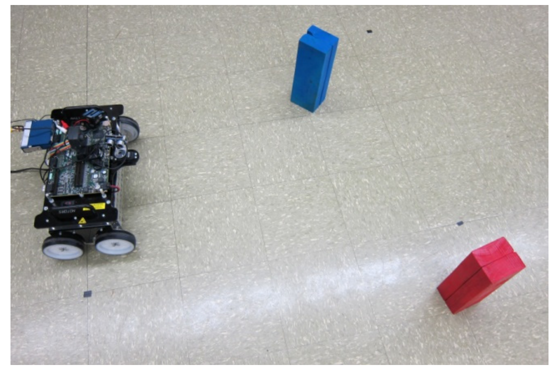


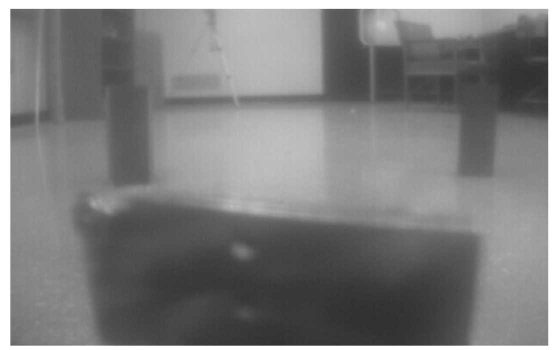
Figure 4: Flowchart of robot program in example system simulation.

Image processing of camera data plays an important role in cognition process and hardware implementation. The system shown in Figure 5a) represents a simple autonomous microgrid problem of finding and connecting a power source (red block) to a power sink (blue block). A camera snapshot is illustrated in Figure 5b). The first step in identifying obstacles from a snapshot is to window the pixels to those likely to contain objects, which helps to eliminate noise and background clutter. The second step is to average the pixels vertically. A single-dimensional array with obstacles showing up as 'darker' valleys against the background is produced when obstacles tend to fill the window. Then a low-pass filter is employed to eliminate the high-frequency ripple caused by the chrominance dots. The resulting sequence is a good estimate of brightness, with the obstacles being clearly discernible. Figure 5c) shows this sequence for the image in Figure 5a). Note the obstacles at 120 and 535 pixels. These can then be located using a peak-detection algorithm.

a)



b)



c)

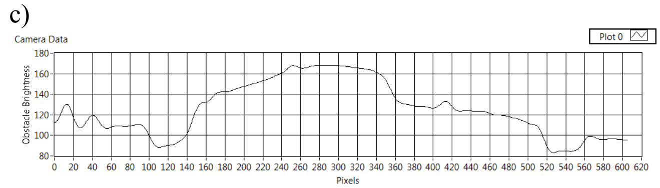


Figure 5: a) Autonomous system and the two colored targets. The red block represents a power source while the blue a power sink. b) Camera view of the robot. c) Target detection from camera.

The algorithm can tolerate uncertainty in environment and measurement corruptions and mobile robot accomplishes the task reliably. For example, the sonar used for ranging, can have a problem at short range, which is compounded by errors in dead-reckoning position and the vision system can have angular errors making mobile robot fail to recognize the obstacles, however the results of simulations illustrates the efficiency of the developed software structure as seen in Figure 6. Figure 6 shows a power converter robot reaching and connecting a stationary power source node and a stationary power load node shown as colored targets.

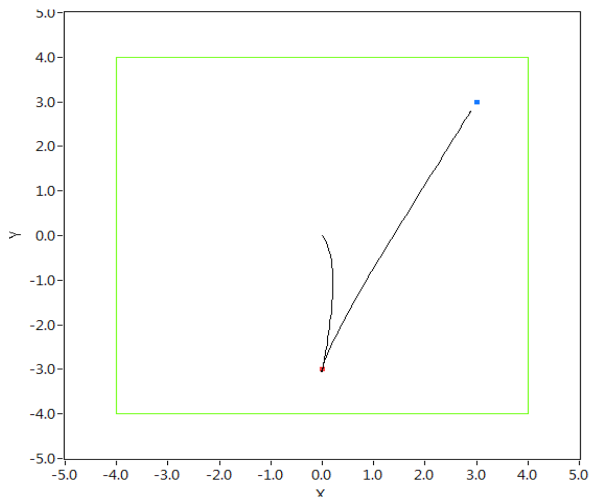


Figure 6: Simulation path results of a power converter robot reaching and connecting a stationary power source node and a stationary power load node.

There are many options for physical connection between the nodes, including direct electrical connectors similar to banana jacks, or a rail system. With a rail system around the parameter of the robot the exact lateral positioning of the robots is not necessary. A clamp or hook could be mounted at the height of the power connection rail of the converter robot. Figure 5 shows a step by step isometric interpretation of the hardware implementation. In Figure 5a) the converter robot moves to the source and connects a power cable, then in b) the converter robot moves and connects to the load. In Figure 5c) the generation robot move and connects to the converter robot. The next step is to start up the electrical generation and conversion process to deliver power to the load.

ELECTRICAL POWER SYSTEM CONFIGURATION AND OPERATION

During the physical positioning and connection of the mobile and stationary nodes, they also communicate their individual terminal voltage characteristics. The mobile converter robot will use this information to structure the control system of the internal converter structure. See Figure 6 for the illustration of the concept. The mobile converter node robot contains a battery pack, a capacitor, and 6 "power pole" legs. Each leg can be used as either a step up dc to dc converter, or using 3 legs as an *ac* to *dc* converter. The internal bus of the node A has a nominal voltage of *600* V_{dc} which is above the level of all other nodes and thus is used as a universal voltage conversion step. The power from the solar panel array is at *200* V_{dc} and the voltage to the stationary load is at *200* V_{dc}. Therefore, leg "A" will operate as a step-up boost converter, leg "B" will be a step-down buck converter, legs "C", "D", and "E" will operate as a three-phase ac to dc converter and leg "F" is connected to the battery. The battery on the mobile converter node is used for bulk energy storage and is useful for voltage support of the *600* V_{dc} bus. Legs "A" through "E" could be re-configured in any connection arraignment as long as the control system knows the input voltage type and magnitude at the time of connection.

a)

b)

c)

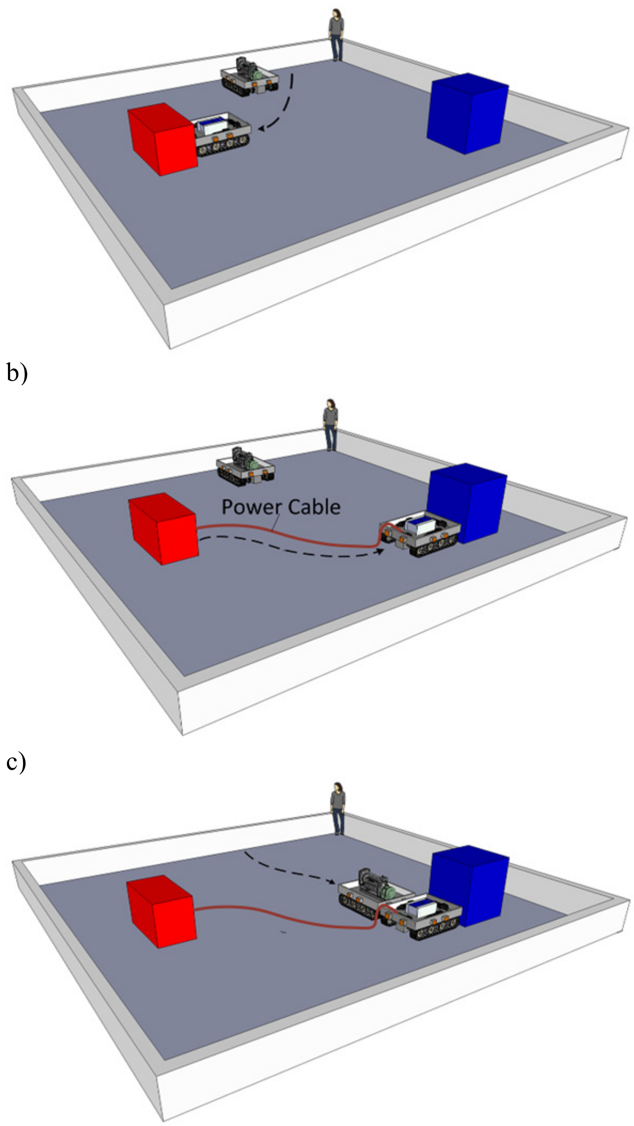


Figure 5: Example system robot movements. a) Converter robot connects power cable to source (red). b) Converter robot moves and connects to load (blue). c) Generation robot moves and connects to converter robot.

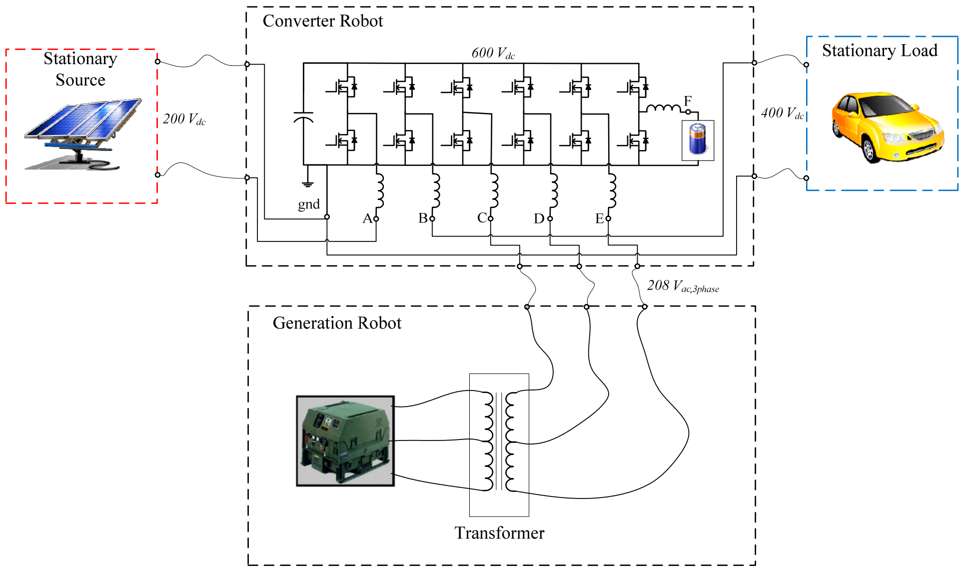


Figure 6: Electrical schematic and configuration of illustrative example system.

CONCLUSIONS

In this paper an electric power prepositioning system using small autonomous swarm robots each containing a power electronic building block is proposed. With this approach the system is highly reconfigurable and robust. This concept is highly scalable beyond the two node example presented in this paper. For example, a large power network of dozens of power sources and loads could be interconnected with multiple connection/converter robots and serviced by many generation and renewable energy robots. If loads, generation, or other assets change then the nodes can physically and electrically reconfigure to meet the new demand or generation opportunities. One challenge to overcome is the servicing of critical loads that cannot be interrupted. In this case the nodes will need to maintain service to these loads using a parallel handoff procedure, while physically re-configuring to meet the demands of lower priority loads. In addition, energy storage nodes that use batteries, flywheels or other technologies will play a critical role as they can be used to buffer renewable energy resources over operational cycles, as well as serving as uninterruptible power supplies to critical loads during system re-configurations.

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