A Test-Environment for Control Schemes in the Field of Collaborative Robots and Swarm Intelligence

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Abstract[1]

This paper presents an architecture for a test-environment for algorithms and control schemes in the field of collaborative robotics and swarm intelligence. As the foundation of the test-environment, small bionically inspired robots are presented. The robots are small (20 cm x 5 cm x 5 cm) and lightweight (< 200 g). Their design is inspired by the movement of caterpillars. Three cubical segments are connected via special joints, where each of these joints has three independent degrees of translatory freedom. Thus, the robots are able to handle rough terrain with small obstacles. The robots are driven by innovative piezoelectric motors that allow a gearless design without any rotary parts. Each robot is equipped with on-board processing and radio communication. The software of the robots is written using TinyOS, an event-driven operating system for large-scale distributed sensor-actuator-networks.

1. Introduction

A group of robots has several advantages over a single one, which enables a group of robots to solve certain tasks more efficiently than a single robot. Firstly, a group of robots has the advantage that it has different viewpoints simultaneously. This is especially beneficial if time variant distributed phenomena are to be monitored. Even a single robot with sophisticated sensing abilities is typically not able to record data at different locations simultaneously, but needs to move around. Secondly, a group of similar robots is very robust due to redundancy. If one robot fails, the mission as a whole is not jeopardized as other robots can assume the task of the malfunctioning one. In addition, a group of robots is very well scalable. Many distributed tasks (e.g. maintenance tasks like room cleaning or monitoring tasks in industrial plants or sewer systems) can be done much quicker by a larger group of robots. Thus, the number of deployed robots can often be adapted dynamically depending on the size of the task.

In order to develop and test the necessary algorithms for cooperative robots, it is imperative to not only rely on simulations, which are certainly a necessary tool, but also to run tests with real robots under real world conditions. The center of any such test-environment are obviously the employed robots. Their features and abilities determine the capability of the overall system. To be able to test the developed algorithms in a real world scenario, the robots have to be able to handle conditions similar to the real world, i.e., they have to be able to operate on a variety of different surfaces and have to be able to cope with small obstacles.

Several of the robotic systems currently employed as the basis for test-environments in the field of cooperative robotics or swarm robotics are wheel based [1–3]. This technology, which is fairly easy to build and operate, has the disadvantage that these robots are typically not able to handle difficult surface conditions or small obstacles resulting in the fact that real life situations cannot be simulated. There are also systems that operate with rubber tracks, which increases their ability to handle difficult surfaces [4]. Still, these systems are only intended to cope with slightly uneven surfaces like rugs, but are unable to handle obstacles. Most of these robots are intended for operation on flat surfaces. A system called SWARM-BOT uses a different approach [5]. This system is intended to cope with uneven surfaces and obstacles by cooperation of different robots. This, of course, generates a significant amount of cooperation overhead just for locomotion. A typical approach to cope with uneven surfaces is to build legged robots. This leads to robots that are able to handle rough terrain and obstacles very well [6, 7]. On the other hand, these robots

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have such demanding mechanics and are so difficult to control that they are not suited for applications in cooperative robotics, where the individual robots must not surpass a certain level of complexity.

In this paper a test-environment for cooperative robots is proposed that is based on robots, which are able to handle rough terrain with small obstacles like those that can be found in a normal household situation. Still these robots have a quite simple and robust design consisting of three cubical segments, which are connected via special joints, where each joint has three independent degrees of translatory freedom. The design is inspired by the motion of caterpillars.

The remainder of this paper is structured as follows. The next section describes the objectives for the design of the test-environment. Section 3 describes the design of the robot, on which the proposed test-environment is based. Details on the technical realization of the robot are given in Section 4. The technical realization of the proposed test-environment is described in Section 5. Conclusions and some details on future investigations are given in Section 6.

2. Design Objectives for the Test-Environment

The main objective of this work is to build a test-environment for algorithms and control schemes in the field of collaborative robotics and swarm intelligence. The goal is to build a system that allows to stage test scenarios that are similar to real world situations.

Due to this, several requirements have to be met. The employed robots, which form the basis for such a system, have to be able to cope with real world conditions like uneven surfaces or small obstacles, as they might occur in any household situation. To keep the system as a whole manageable and to reduce its production cost, the complexity of the system has to be kept to a minimum. This leads to the desire of keeping the design of the employed robots simple and cheap enough to allow their volume production. Additionally it is important for the system to be able to withstand an everyday testbed situation.

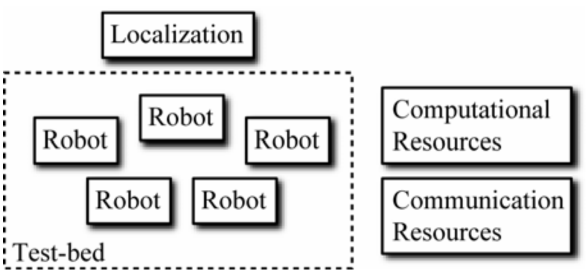

Figure 1. Building Blocks of the Proposed Test-Environment

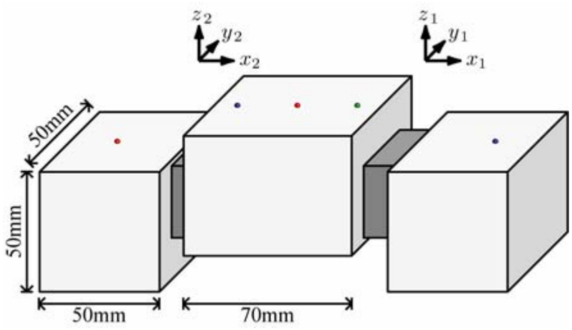

Figure 2. Schematic of Fully Cladded Robot

Next to the ability of the robots to move, which is an inherent feature of the robot, certain other important features need to be realized in such a test-environment. These include localization, computational resources and communication resources (figure 1). All of these features can be integrated into the robots, but it is also possible to decouple them partially from the robot and to just make them available to the robot.

3. Robot

The employed robots form the basis of any test-environment for algorithms and control schemes in the field of collaborative robotics and swarm intelligence. To keep the complexity of the test-environment to a minimum and to reduce production costs, multiple identical robots are employed.

3.1. General Setup

The proposed robot consists of three segments (figure 2).

These segments are connected by a special set of joints that each have three independent translatory degrees of freedom.

Therefore, the robot has a total of six independent degrees of freedom. The head and the tail element are identical, so that if the robot changes direction, the tail becomes the head and vice versa.

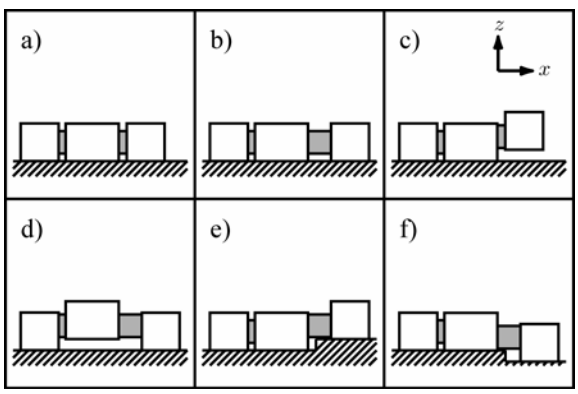

Figure 3. Selected Configurations of the Robot (Side View): a) Basic Configuration, b) Head Extended, c) Head Raised, d) Middle Segment Raised, e) Head up a Step, f) Head Down a Step

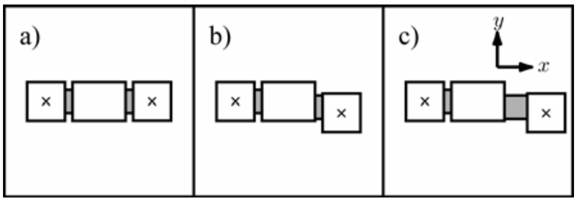

Figure 4. Selected Configurations of the Robot (Top View): a) Basic Configuration, b) Head to the Right, c) Head Extended and to the Right

In figure 3 and figure 4 some of the possible configurations of the robot are depicted. Each joint can be extended or contracted (e.g. figure 3 b). Additionally each segment can be lowered or raised with respect to the adjoining segment (figure 3 c-f). This design allows the robot to cope with uneven ground, small obstacles or steps (figure 3 e-f).

Aside from these movements, the robot is also able to move each segment sideways (figure 4). This is especially important for rotation and sideways movement.

3.2. Motion Patterns

The design of the robot permits a wide variety of motion patterns. Some basic ones are described below. The most efficient motion can be generated by a superposition of the basic motion patterns.

Walking

The most basic motion pattern is walking. In this mode the robot moves its segments one by one in the desired direction (figure 5). This way the robot can move in a straight line either forward or backward. During this motion typically no slipping occurs.

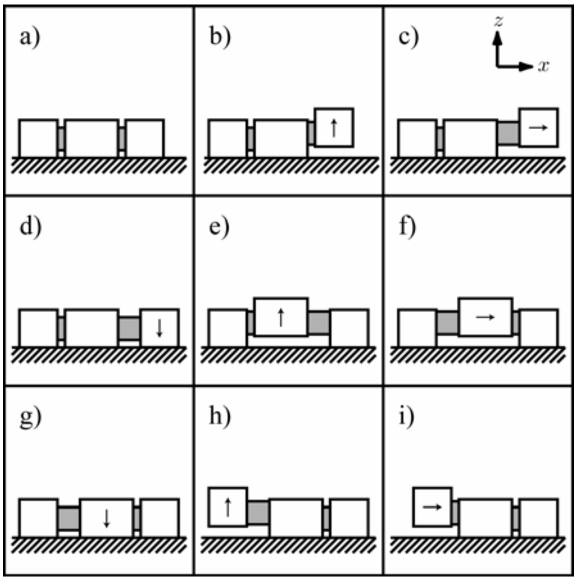

Figure 5. One Step of the Robot (Side View): a) Initial Configuration, b) Head is Lifted, c) Head is Moved Forward, d) Head is Lowered, e) Center is Lifted, f) Center is Moved Forward, g) Center is Lowered, h) Tail is Lifted, i) Tail is Moved Forward

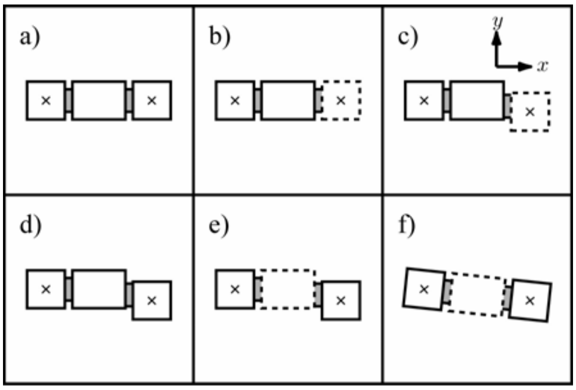

Figure 6. Rotation of the Robot (Top View): ***Dashed Lines Indicate Raised Segments*** **a) Initial Configuration, b) Head is Lifted, c) Head is Moved to the Right, d) Head is Lowered, e) Center is Lifted, f) Center and Head are Aligned, the Robot Rotates**

Rotation

In order to change direction, the robot can rotate. During this motion one of the end segments (head or tail) is moved in the desired direction of rotation (figure 6 a-d). For an even faster rotation, it is also possible to move the other end segment in the opposite direction. The middle segment is raised in order to decrease friction and then the end segments that have been moved to the side are realigned with the middle segment (figure 6 f). This leads to a rotation of the robot with the end segments as anchor points (indicated by the crosses in figure 6).

Besides these most basic motion patterns other step sequences, e.g. for a sideward motion or a faster running motion (head and tail are moved simultaneously), can be realized with the proposed robot design. One major advantage of this design, next to the ability to cope with uneven ground and small obstacles, is the fact that very little slip occurs during the movement. This is the case as in most situations two segments of the robot are motionless on the ground. Therefore, this design is well suited to acquire odometric data.

4. Technical Realization of the Robot

In order to build a robot as described above, several design challenges have to be met. While maintaining extremely low weight, the whole construction still has to be strong enough to withstand an everyday testbed situation. Additionally the design has to be simple and cheap enough to allow volume production. Next to the desired small size, this leads to the need of very precise and automated manufacturing processes. A special problem is the design of the joints. These joints have to be built in such a fashion that all three independent translatory degrees of freedom can be realized.

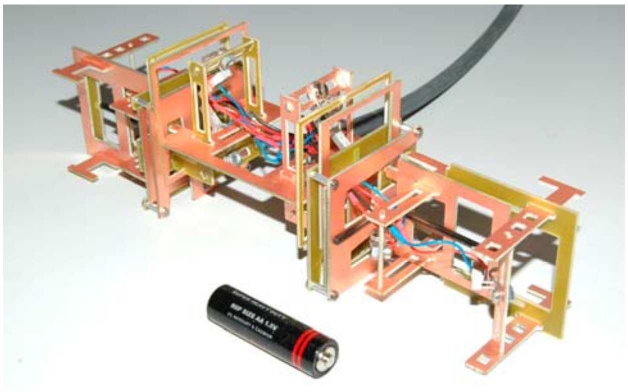

Figure 7. Inner Structure of the Robot with Motors in Comparison to an AA battery. A Video of the Robot in Motion can be Found at [9]

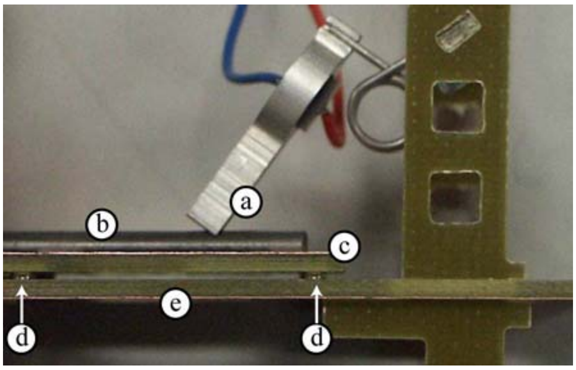

Figure 8. Linear Sliding Carriage: a) Piezoelectric Motor, b) Carbon Fiber Reinforced Plastic Rod, c) Sliding Carriage, d) Ball Bearing, e) Base Plate

4.1. Dimensions

The head and the tail of the robot have the exact same design. The centre segment is slightly longer. Each segment has a width and height of 50 mm. The head and tail have a length of 50 mm as well. The centre segment has a length of 70 mm. With the additional size of the joints, this results in a contracted length of 200 mm. If the joints are extended, the total robot has a length of 240 mm.

The head can be moved up to 20 mm to the front (x_1 in figure 2), up to 17 mm to each side (y_1) and it can be raised or lowered up to 17 mm (z_1). The movement range of the tail is identical due to the symmetrical setup.

The robot has an overall weight (including batteries, etc.) of less than 200 g.

4.2. Mechanical Hardware

The mechanical inner structure (figure 7) of the robot is built from an epoxy resin glass laminated fabric with a thickness of 1.5 mm that is copper plated at one side. This material is also used to build printed circuit boards. Besides the high strength and the low weight of this material, it can be cut and milled very precisely with a CNC circuit board plotter. In our case we use an LPKF C60 circuit board plotter with a step resolution of 1µm and a repeatability of ±1µm [8]. Due to the fact that a computer controlled tool is used, the mechanical components can be produced automatically with very high precision.

The use of the copper plated material has the added advantage that the electrical components can be built directly into the mechanical structure of the robot. Therefore, a high level of system integration can be achieved.

Actuation

The robot is actuated by 8 piezoelectric motors from Elliptec Resonator AG [10]. The piezoelectric motors have been chosen for their low weight (1.2 g) and their ability to generate direct linear motion without the need of a gear. Additionally their short response time (100 µs) and their relatively high speed (up to 300 mm/s) is advantageous.

For the lifting of an element (z_1 and z_2 in figure 2), two motors are used in parallel. The other degrees of freedom are actuated by a single motor.

The employed motors have a very simple design that just consists of three parts (an aluminum frame, a piezoelectric stack and a spring). They are driven with a pulsed voltage of $\leq$ 2.5 V at two different frequencies (typically 79 kHz and 97 kHz) for forward and backward motion, respectively.

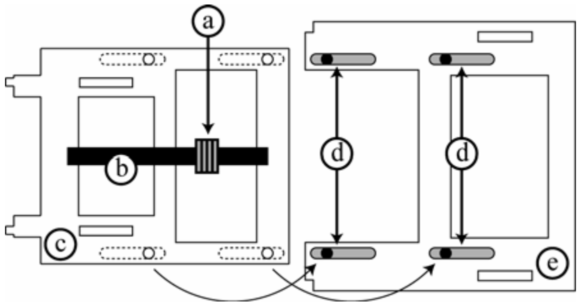

Figure 9. Schematic of Linear Sliding Carriage: a) Contact Point of Motor, b) Carbon Fiber Reinforced Plastic Rod, c) Sliding Carriage, d) Grove of Ball Bearing, e) Base Plate

The applied pulsed voltage causes the tip of the motor (figure 8 a) to vibrate in an elliptic fashion. Depending on the frequency used, the elliptic rotation of the tip of the motor is clock- or counterclockwise. This motion can be directly applied to a carbon fiber reinforced plastic rod (figure 8 b) that is moved forward or backward accordingly. This rod is fixed to the linear sliding carriage (figure 8 c) that is to be driven. This carriage is bedded on four ball bearings (figure 8 d) on a base plate. This is done in order to reduce friction, which is important because the functioning of the motors relies on friction as well. The ball bearings are realized with four pairs of milled groves on the sliding carriage and the base plate that each takes one steel ball with a diameter of 2 mm (figure 9).

All six translatory degrees of freedom of the robot are built with this design. One joint (with three degrees of translatory freedom) is made up of three sub-assemblies as described above. The sub-assemblies are connected in a perpendicular fashion to realize the independent degrees of freedom.

4.3. Electronic Hardware

The electronic system of the robot is split into three parts, the main controller board and two motor controller boards. The main controller is located in the center segment of the robot, the motor controllers in the head and in the tail. The motor controllers are connected to the main controller with a two-wire communication protocol.

The main controller is used for the high-level control functions of the robot as well as for radio communication. The motor controllers provide the signals needed for the piezoelectric motors.

Main Controller

A wireless sensor module called Telos from Moteiv is used as the main controller [11]. This module is typically intended as a node in sensor networks, but it is also very well suited for applications in swarm robotics. It is equipped with a 16-bit Texas Instruments MSP430 micro controller with a clock rate of 8 MHz, 10 KB RAM and 48 KB Flash memory. Therefore, computational and memory resources are available in the robot that allow onboard execution of complex control algorithms. Additionally the micro controller comprises a wide variety of interfaces (e.g. 12-bit DAC, 12-bit ADC and I^2C), which can be used for different sensing tasks. The radio communication is done with a 250 kbps 2.4 GHz IEEE 802.15.4 Chipcon Wireless Transceiver (ZigBee). With the integrated antenna, an indoor range of up to 50 meters can be realized. The main controller uses TinyOS [12] as its operating system. TinyOS is an event-driven operating system for large-scale distributed sensor-actuator-networks and is therefore very well suited for the programming of these kinds of robots. It also has the advantage that the necessary radio communication functionalities are included.

Motor Controller

The motor controllers are equipped with the same micro controllers as the main controller. These micro controllers are used to generate the necessary pulsed voltages for the motors. Additionally, an amplifier circuit is employed to provide the necessary voltage levels as well as the necessary electrical currents. Because the computational resources of the employed micro controllers are not exploited entirely, these controllers can be used very well for additional control or sensing tasks in the future.

5. Technical Realization of the Test Environment

The robots are integrated into a control-environment. Although the robots are quite rich in computational resources, the high-level motion control is currently computed on an external control computer. This is done mainly in order to be able to use high-level mathematical languages (e.g. MATLAB) to implement the high level control algorithms, which is very convenient for research purposes.

Camera Tracking of the Robots

Most control algorithms rely on knowledge of the posture, i.e., the position and orientation, of the individual robots.

Therefore, it is important to localize the robots. This can be done with systems built into the robots [4]. As such integrated systems lead to quite a significant amount of technical overhead that needs to be built into the robots and as they typically directly affect the way the robots have to be controlled, an external camera-based system to track the robots is employed.

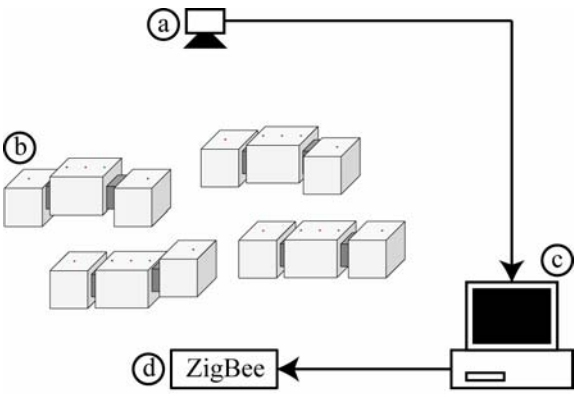

Figure 10. Test-Environment: a) Overhead Camera, b) Robots, c) Control Computer, d) ZigBee Transceiver

The test area is observed with an overhead CCD color camera (figure 10 a). This camera has a resolution of 1024x768 pixels and observes an area of 2.4 m x 1.8 m. This results in an usable resolution of about 5 mm. The theoretical resolution, which is obviously higher, is reduced due to distortion and blurring. The position of the individual robots (figure 10 b) is extracted from the images by a feature extraction software that is executed on the central control computer (figure 10 c). In order to facilitate the posture extraction of the robots from the image and to be able to identify the individual robots, five LEDs are mounted on top of every robot.

The position of the individual robots (figure 10 b) is extracted from the images by a feature extraction software that is executed on the central control computer (figure
10 c). In order to facilitate the posture extraction of the robots from the image and to be able to identify the individual robots, five LEDs are mounted on top of every robot.

Test Area

The test area can be used to stage a variety of different scenarios important to cooperative robotics research. For example it is possible to construct a path with various surmountable and insurmountable obstacles and different surfaces. A group of robots has to move via this path to a given target point most efficiently. Another possible scenario is a search task for a group of robots in an environment that resembles a normal household situation.

6. Conclusions and Future Works

In this paper we presented an architecture for a test-environment for algorithms and control schemes in the field of collaborative robotics and swarm intelligence. Besides the necessary infrastructure for tracking, computation and communication we proposed a novel robot design that is bionically inspired by caterpillars. The robot consists of three cubical segments that are connected via special joints. Each of theses joints has three independent degrees of translatory freedom. Robots with this design are expected to be able to cope well with difficult surface conditions and small obstacles.

Future work will include the integration of internal sensors into the robots to improve the controllability of their movement, the integration of different ambient sensors into the robots and the integration of systems for self-localization of the robots. The test-environment is additionally planned to be employed for the evaluation of different kinds of control schemes in the field of collaborative robotics.

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