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DISTRIBUTED MECHATRONICS CONTROLLER FOR MODULAR WALL CLIMBING ROBOT

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ABSTRACT

Practical wall climbing robots that are used for applications requiring them to be fitted with task specific tools should be large enough to carry the additional tool payload. As size of robot is increased, inflexible body frame of wall-climbing robot limits its capability to change surfaces and to maneuver on uneven surfaces. In this paper, modular design of wall-climbing robot implementing two articulated legs per module (biped robotic modules) is presented. The design improves robot's maneuverability and flexibility when changing surfaces or whilst walking on uneven surfaces. The minimum number of sensors and actuators in each module is fifteen. As the number of modules used in the design of the robot is increased, the number of actuators and sensors increase exponentially. Distributed mechatronics controller of such systems is presented. There is a limit of the number of modules that can results in practical operation of the wall-climbing robot. The developed control system uses three layers of message prioritization in order to control and schedule robot's tasks.

1. INTRODUCTION

A module of a robotic system is defined as any functionally complete device that can be independently operated and can be readily fitted and connected to, or in combination with, additional modules to comprise a complete and functionally reliable system (Virk 2003). Some advantages of modular designs of robotic system are flexibility to changing environmental needs, low-cost due to standardization of the modules, inter-connectability and inter-changeability of modules with each other, and improved system reliability due to modular architecture (Zhuming, 2002). Standardization in modular design of walking robots (hardware and software) is being undertaken in the CLAWAR project in Europe.

A massively distributed control system for modular reconfigurable robot has been developed by (Zhang et al 2002) implementing CAN bus. However, this is developed for robotic system that consists of more than 10 modules. Higher communication layers were developed so that messages on the CAN bus can be managed using buffers, to improve multi-threading capability in order to improving hardware resources allocation, and to manage multi-master/ multi-slave structure of modules. In this paper, we show how to develop a distributed control system for modular wall-climbing robot that consists of less than 10 modules. We use finite state machines to control the sequential tasks of the robot. This is also used to determine which CAN bus messages must be implemented, and which module must produce the CAN message. Real-time control of time-critical tasks, such as servo-motor control, are left to the local module microprocessor i.e. smart module are used. Some other proposed applications of CAN bus in the field of robotics include: improvement of software design of distributed mechatronic systems (Chen 2001) and design of modules for modular parallel robots (Yang et al 2001).

Repetitive tasks have been automated using robotic systems in order to reduce the operational time, improve quality and flexibility of manufacturing systems. Most of such tasks and their environments usually require horizontal surfaces. However there are many tasks such as cleaning of high-rise buildings, inspection and maintenance of storage tanks, etc which are normally conducted at steep slopes or vertical surfaces. The environments of such applications can be dangerous to human operators. This will inevitably reduce the efficiency and increase the cost of performing such operations.

Mobile wall-climbing robots that have the capability to carry tools and equipment to perform the required tasks provide a more cost effective solution to the problem (Luk et al 1991). Such robots are termed service robots by the International Service Robot Association (ISRA) (Pransky 1996). They are defined as machines that sense, think, and act to benefit (or extend) human capabilities and to increase human productivity.

A mobile robot with the capability of climbing walls or other inclined surfaces and carrying out various tasks must be light enough so that its weight does not strain the structure, yet rugged enough to work in an exterior environment and powerful enough to carry the necessary payload. It must also have the ability to climb over obstacles since the various surfaces like building walls, etc. will normally have protrusion such as pipelines, window frames, etc and to maneuver reliably within an undefined environment. It must be able to change surfaces e.g. changing between perpendicularly juxtaposed walls, or maneuver on uneven walls e.g. a curved wall. Clearly, wall-climbing robots need not be able to undertake all of these tasks and some applications may require only one or two such capabilities. In this paper, a modular design of wall-climbing robot is presented in order to solve these problems.

The developed modular wall-climbing robot implements biped robotics systems as its modules. Each biped robotic system consists of two articulated legs. The minimum number of actuators and sensors in one biped module is thirteen. Addition of modules increases the number of actuators to be controlled and the number of sensors to be monitored exponentially. This presents challenges in the design of the controller for such mechatronics systems. Implementing a central microcontroller system (embedded control system) will result in hard to-trace, untidy connection wires. Troubleshooting and software code to control the robot will be very difficult to develop. Real-time control of the developed wall-climbing robot becomes complicated due to many actuators and sensors. In this paper, a distributed mechatronics controller of such system is presented. The controller is based on Controller Area Network (CAN) technology. Disadvantages of distributed control systems are the delays introduced in the systems because of distributed control architecture. This includes problems that are concerned with timing, such as lag effect of zero-order hold (ZOH) and problems with respect to motion control. Problems of time variations can also be partially tackled in control design, e.g., by using robust control so that deviations from nominal timing can be tolerated (Chen 2001).

2. VERTICAL SURFACE ATTRACTION AND TRANSLATIONAL METODS IN WALL-CLIMBING ROBOTS

One of the first steps in designing wall-climbing robot is to decide on the technique that will be used to safely adhere robot to vertical surfaces. Three techniques have been implemented in different designs of wall-climbing robots:

- Vacuum suction implementing pneumatic suction cups; used on non-ferrous, smooth surfaces such as glass (Briones et al 1994),
- Magnetic suction using an electromagnet or a permanent magnet; used on ferrous or magnetic surfaces, such as boilers (Naitou 1992), and
- Vortex attraction implementing a mechanical device that forms vortex; used on any surface (Clarifying Technologies 2004).

Another design consideration for wall-climbing robots is a technique that is employed in order to achieve its motion. Techniques that have been used are: articulated legs, sliding frames, tracked propulsion and wheeling mechanisms. Articulated legs move by keeping a grip on the surface with some of its legs whilst moving its free legs further up the surface. By repeating this motion, multi-legged robots can climb (Nagakubo et al 1994). Sliding frames robots have two or more body platforms that are linked to each other by a prismatic joint so that they can slide against each other. One platform of the body stays gripped in place whilst the other releases its grip from the surface, slides itself in the desired direction and then reattaches (Gradetsky et al 1992).

By adding the ability for the central platform to rotate, sliding frames can move both up and down, and left and right. This allows the robot to have more degrees of motion for adapting to the complex wall geometries. Tracked propelled vehicles use a loop of track to grip the ground and move forwards or backwards. Sometimes this motion can help robots change surfaces (Nishi and Miyanga 1994). The movement of the climbing robots using walking or translating mechanisms is discontinuous due to the operating mode of sticking-moving-sticking. To overcome this shortcoming, the mechanisms using wheels or crawlers have been employed for some wall-climbing robots (Nishi 1992).

The design of the service robot described in this paper uses vacuum suction created by vacuum pumps and vacuum cups. The high strength to mass ratio of vacuum systems is desirable as it improves safety of the wall-climbing robots. Articulated legs are used to improve the developed wall-climbing robots maneuverability and flexibility. The robot ability to changes surfaces is improved by the modular design (refer Figure 3 (a)). Each articulated leg has a suction cup that helps the robot to adhere to smooth surfaces. This gives the robot the capability to walk on vertical surfaces as enough vacuum pressure is maintained in the suction cups. Two miniature suction pumps are used to create and maintain vacuum in the suction cups when they make contact with a smooth surface. Each suction pump has been tested and can carry more than 3 kg. The pressure in the suction cups is regulated by miniaturised micro-valves. The valves can set the pressure in the vacuum cups to be either vacuum or atmospheric pressure. The use of vacuum suction cups limits the application of the developed wall-climbing robot to smooth surfaces only.

3. MECHANICAL DESIGN OF BIPED MODULES

The wall-climbing robot developed in this paper is inspired by insect's anatomy. Insects have segments that allow their bodies to be flexible. This allows insects to easily maneuver and maintain stability while climbing uneven surfaces. The robot implements articulated legs that consist of four joints each, that are each actuated by a DC servomotor (motor 1 to motor 4). This arrangement gives each leg three degrees of freedom (DOF) (refer Figure 1). Motor 4 is a redundant motor i.e. does not contribute additional DOF. Its purpose is to maintain a certain pose of the vacuum suction cup when the leg is making contact with the surface.

Other walking hexapod or quadruped robots that have been developed, normally use a parallelogram mechanism to achieve this. They have only one motor per each articulated robot leg and have only one body. Although the one-motor-per-leg and one stiff body are enough to achieve locomotion, it is not enough to achieve smooth motion with minimized friction. This is because all the legs are mounted on one frame. As the legs of the robot are moving in order to cause change in the displacement of the robot's body, the robots frame is changing its posture and orientation. Since the frame is not elastic, it does not bend to allow the legs that have made contact with the ground to maintain their original posture when they first made contact with the ground. This causes the parts of the legs, which are in contact with the ground to slip, and hence loose efficient contact with the ground. Any movement of the robot's frame is propagated to the tip of the articulated leg that is making contact with the surface. This can result in loss of vacuum pressure in vacuum cups of wall-climbing robot.

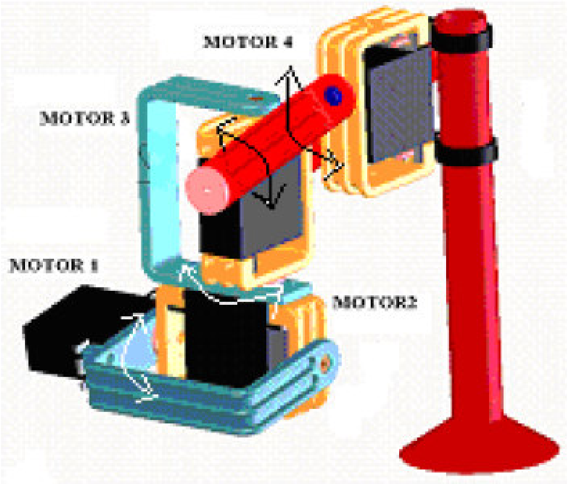


Figure 1. Articulated leg of the biped module.

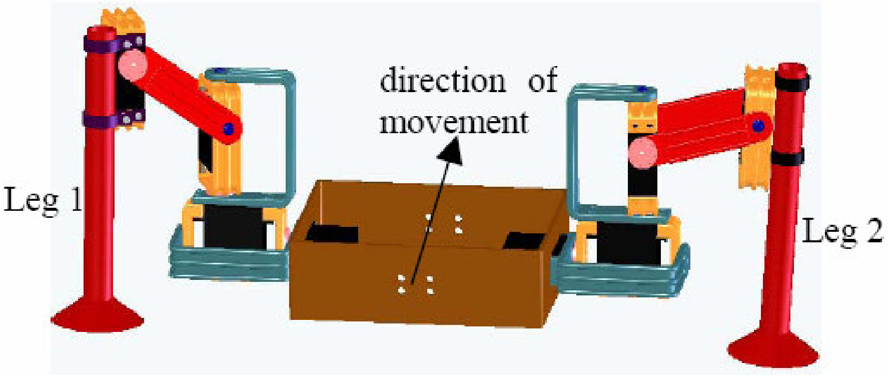


Figure 2. The biped module for wall-climbing

The first motor is attached to a base, which in turn is attached to the body frame of the biped module (refer Figure 2). Purpose of the motor is to rotate the complete leg enabling the robot to change the walking surface e.g. from floor to wall. The first motor drives the second motor's housing. The purpose of the second motor is to move the rest of the leg forwards and backwards during locomotion. The second motor drives the housing of the third motor. The purpose of the third motor is to move the fourth motor and the suction cup up and down during locomotion. The fourth motor and the suction cup are attached on the same housing. Purpose of this fourth motor is also to move the suction cup up and down during the locomotion of the robot. The third and the fourth motors act together to achieve a smooth contact surface between the suction cup and the surface that is being moved upon.

In order to assemble wall-climbing robot that consists of any number of biped modules, each biped module, except the first module in the assembly, is fitted with a motorized revolute joint at the front. The joint gives the two modules attached to it one DOF. This gives the developed wall-climbing robot the ability to change surfaces easily (refer Figure 3). The overall motion of the robot (or gaits) is planned according to the number of modules that comprises the robot while maintaining robot's stability according to criterion mentioned in the section that follows.

The body frame has been constructed out of aluminum in order to minimise mass. All the parts of the designed robot have been manufactured on the Dimension rapid prototyping machine. The developed design of wall-climbing robot is shown changing surfaces in Figure 3 (b). The ribs were added to the robot parts to give them strength and robustness. One module of the developed robot prototype weighs just over 2 kg. The body frame also houses the electronics, sensors and all the other associated equipment depending on the application tasks.

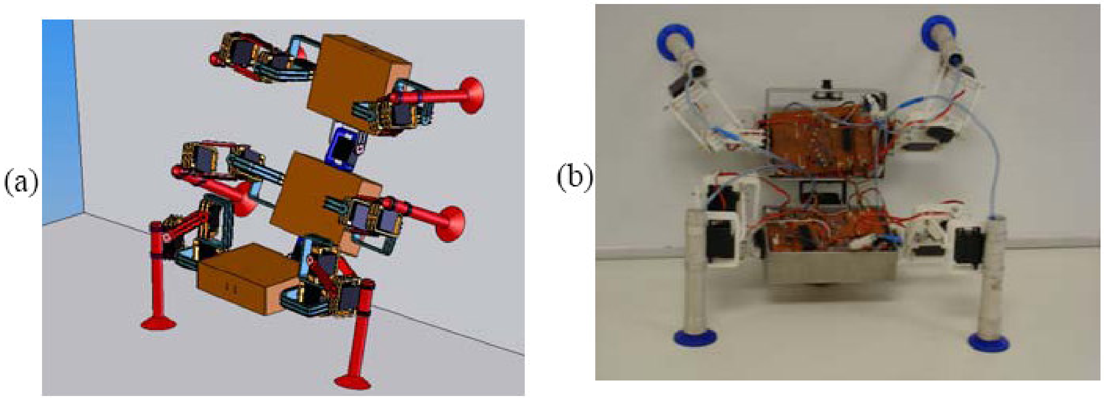


Figure 3. (a)Concept of Modular-Wall-climbing Robot (b) Developed Design of Wall-Climbing Robot.

3.1. DESIGN FOR CONTROL

In order to simplify the problem of controlling the wall-climbing robot, inherent stability is taken into consideration in the mechanical design. The biological mechanisms of many specialised climbing creatures have shown one common characteristic. The limbs of the creature leave the body in such a way that the creature's belly may be close to the ground while it is in motion. For example, in beetles this is achieved by a wide spread of the legs, often exceeding to more than three times the body width.

In spiders the body hangs below the 'knees' and the limbs can adduct to a little more than the body width and still maintain stability (Luk and Billingsley 1991). An upper-and-over spider-like arrangement appears to have better potential for negotiating obstacles. The body can be raised and lowered and the reach of the legs can easily be made to exceed the body length. Such an arrangement will help in negotiating obstacles and provide the desired stability to the mobile robot. In the proposed wall-climbing robot this is achieved by raising the knee joint of the robot leg, joint of second and the third motor, from the biped robot module's body level and increasing the height of the rod which connects the suction cup to the rest of the leg, to give the module strength and robustness as shown in Figure 2. If the direction of movement of the biped module is into the paper, then Leg 1 is the left leg and Leg 2 is the right leg.

It has been shown that a walking robotic systems using n (> 2) articulated legs to walk on the horizontal ground needs a minimum of three legs to be in contact with the ground i.e. tripod of support as in a chair, in order to achieve static stability (Ting et al 1994). The mass-centre of a walking robot must fall inside this triangle of support formed by its three legs on the ground; otherwise it is statically unstable and will fall. In the quasi-static gait of a robot or animal, the mass-centre moves with respect to the position of the legs on the ground, and the probability of falling increases as the centre of mass approaches the edge of the triangle of support. This probability has been quantified for all n legged-walking robotic systems by calculating the longitudinal stability margin, the shortest distance from the mass-centres to the boundary of the support pattern in front of or behind the robot. The longitudinal stability margin (S) of a wave gait (i.e. a regular, symmetrical gait) normalized for stride length is described by:

$$S = (n_{\text{legs}}/4)\beta - (3/4) \qquad (1)$$

where β is the duty factor, the fraction of a stride period that a leg is in the support phase and n legs represents the number of legs (Song 1984). When $S<0$, the robot is statically unstable.

This criterion for static stability is applicable to robots on horizontal surfaces and whose articulated legs are not adhered to the walking surface. For robots that are walking on inclined surfaces and that are using some form of adherence the surface, the forces on the robot in the plane of motion must balance as well i.e.

$$m.g.\sin\theta = \mu.n_{min}(m.g.\cos\theta + F_{\text{vac\_suc}}) \qquad (2)$$

where m is the robot's mass, g is the gravitational constant, θ is the angle between the horizontal and the robot's walking surface, μ is the friction coefficient between the suction cups and surface, n_{min} is the minimum number of legs in contact with the surface while walking, and $F_{\text{vac\_suc}}$ is the attraction force caused by the vacuum pressure in the suction cups.

The control program of the developed modular wall-climbing robot takes this into consideration in order to achieve static stability of the robot at all the times. Dynamic stability of the wall-climbing robot is not considered due to low walking speeds.

5. SENSOR AND ACTUATOR ARCHITECTURE

The tip of each leg is fitted with an infra-red touch sensor, which indicates when the suction cup has made contact with the surface. Miniature limit switches can be used for this sensing application as well. Each leg is also fitted with a pressure sensor that monitors the pressure in the pneumatic system of each leg. The pressure in the suction cups is controlled by micro-switches.

The front of the first biped module is fitted with one ultrasonic sensor, one CCD sensor and a gyroscope sensor. Ultrasonic sensors are used for object detection. A CCD sensor is used for data visual collection and helps with home position navigation. Gyroscope (or inertial sensor) is used for improving stability and for navigation. One independent biped module consists of nine motors, two micro-valves, two pressure sensors, two infra-red touch sensors, one ultrasonic sensor, one CCD camera and one gyroscope sensor i.e. eleven outputs to be controlled and seven inputs to be monitored. The high number of sensors and actuators used requires that a distributed controller be used because of the reasons given in the earlier sections. Controller Area Network (CAN), MCP2515 CAN controller from Microchip (Microchip Technology 2004), is implemented as a stand-alone distributed control network.

PIC18F442 microcontrollers are used as local controllers on the network's nodes. CAN nodes on different robot's modules and the power connections are connected via a connection plate consisting of the following lines: CANH, CANL, +12V and 0V lines.

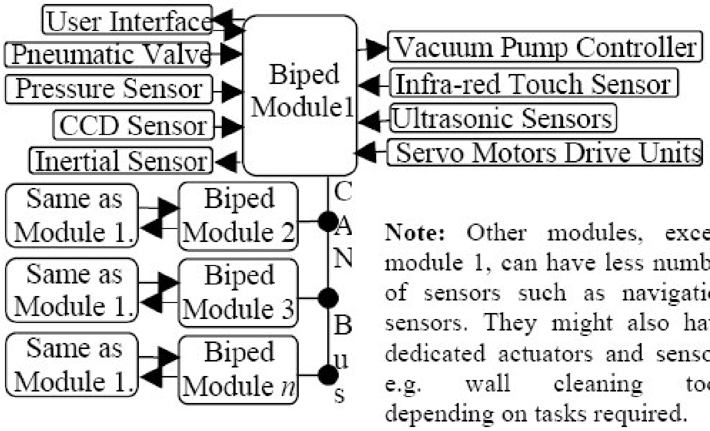
6. DISTRIBUTED MECHATRONICS CONTROLLER IMPLEMENTING CAN

The robot control architecture is divided into time-critical and event-based control strategies. Control functions such as navigation and motion planning are time-critical, while control functions such as path planning and object avoidance are event-based. In order to achieve reliable and adequate control of the robot, Controller Area Network (CAN) is implemented as a mecahtronics distributed controller of the developed modular wall-climbing robot.

CAN has been widely used within the European automotive industry, and the decision for CAN from the US and Japan automotive industry is guaranteed because of the availability of CAN solutions of more than fifty controllers from low-cost devices to high-end chips from more than fifteen manufacturers. Figure 4 shows architecture of a mechatronics distributed controller implementing MCP2515 CAN for controlling modular wall-climbing robot that consists of *n* modules. Figure 5 shows the CAN hardware that was used on each biped module. The attributes of a Controller Area Network (CAN) are:

- The multi-master capabilities that allow building smart and redundant systems without the need of a valuable master,
- The broadcast messaging that is the first piece of the guarantee for 100% data integrity as any device within the network uses the very same information,
- The sophisticated error detecting mechanism and the retransmission of faulty messages which is the second piece of the guarantee for 100% data integrity,
- It comprises of only layers 2 (Data Link Layer) and 1 (Physical Layer) of the International Standardisation Organisation/Open Systems Interconnect (ISO/OSI) hierarchical layered structure (ISO 11519-2 1993), (ISO 11898-2 1993), and
- CAN message data frame which is used is the standard data frame, which consists of eleven message identifier bits and eight data bytes.

Controller Area Network (CAN) is a serial bus system especially suited to interconnect smart devices to build smart systems or sub-systems. CAN bus has been successfully implemented to control PloyPod, which is a modular self-reconfigurable robot (Zhang et al 2002). Due to the high number of robot module used, special higher level software



Note: Other modules, except module 1, can have less number of sensors such as navigation sensors. They might also have dedicated actuators and sensors e.g. wall cleaning tool, depending on tasks required.

Figure 4. The Hardware Structure of the Control System Using Stand Alone CAN.

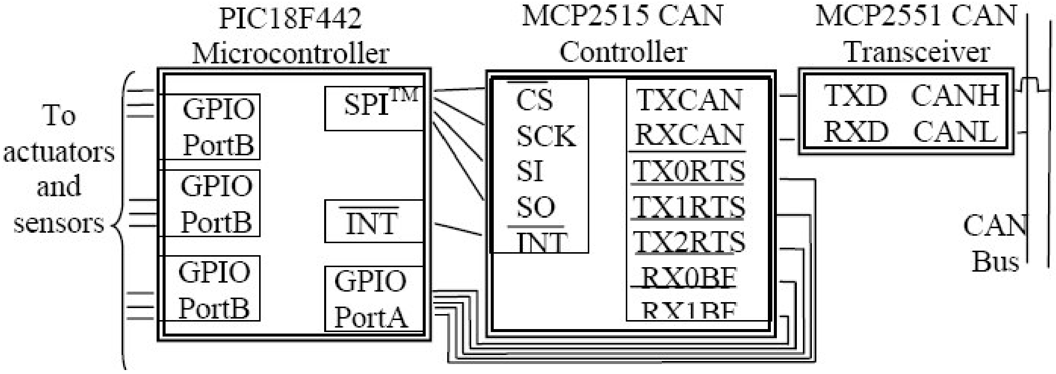


Figure 5. CAN Hardware Implemented on Each Module.

layers were designed in order to manage message queues, multi-master/multi-slave control, etc. In our application, for the developed modular robot to be practical, less than ten (10) modules are sufficient i.e. small scaling. The CAN bus messaging implemented uses broadcast to ensure that all the modules have the same current information. This improves synchronisation of modules, but can reduce bandwidth if more than 10 modules are used. Each module can broadcast its message anytime it has new information. CAN bus message error handling is handled by MPC2515 hardware in a deterministic way. No high level software is needed to achieve proper implementation of CAN bus.

The local microprocessor controls the local actuators and monitors the local sensors. It directly controls the individual movements of each of two six articulated legs of the biped modules. It can indirectly control remote actuators and monitor remote sensors by sending and receiving correctly addressed messages on the CAN bus i.e. by subscribing. Only the messages with message identifiers that have been programmed to be accepted by the local MCP2515 can be used as control data for local actuators. Similarly, the local microprocessor can control remote actuators (on a different CAN node) if the remote MCP2515 is programmed to accept the messages with its message identifiers.

Synchronisation of the movement of the legs is achieved by sending synchronizing messages. Synchronizing messages are divided into three hierarchal layers; top, middle and bottom layers. Figure 6 gives an illustration of the different layers, their priority and time requirements in respect to control. Priority of CAN messages and fast control times increases with the lower hierarchal layer. In CAN, message priority increases as values of message identifiers become low.

The top layer is the layer that contains messages that represent the current task of the robot e.g. robot searching for a certain target using a CCD sensor. This task maybe initiated by the user-interface unit attached to the first module or any other node when the robot is operating autonomously (user-interface consists of wireless radio control unit). This message is then broadcasted on the CAN bus to all the CAN nodes (or robot's modules). Message identifiers are used to identify the kind of message and where it originated. CAN has internal error handling mechanism. If a message experienced error during transmission, this is handled internally by CAN error handling functions. CAN message that experienced error during transmission is re-sent. Thus, it can be known that all the CAN have received the task message or not, and the next step in the control procedure can be implemented. CAN nodes that did not receive a transmitted message will not acknowledge reception of that message.

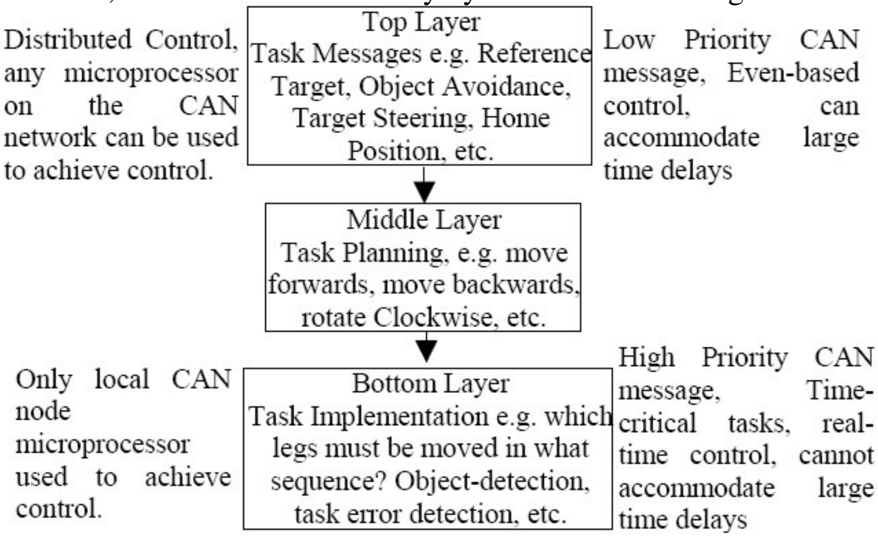


Figure 6. Hierarchal Layer for CAN Messages.

This indicates to the node that initiated a message that the message it tried to transmit on the CAN bus experienced error. The top layer is event-driven and does not get affected by the time delays. Any microprocessor in the distributed control system can be used to achieve stable control of the top layer.

The middle layer is the layer that contains a sequence of movements that are required to achieve the task. After each CAN node has received the message which represents the task to be done, each node will then broadcast a message that contains the sequence of events that are to be done in order to achieve the required task i.e. task planning messages are generated.

CAN node which initiated the message can be indirectly determined by the message identifier. The contents of the message contain the sequence of leg movements to be done. It also contains the information about when and how the specific task actuator is to be controlled if the robot if fitted with that actuator e.g. window cleaning brush actuator. If there are many CAN nodes, this step can be omitted since it will increase the time delays in achieving the robots tasks. Since all the CAN nodes have the same competency, it can be assumed that all the nodes will produce same task planning schedules. Using the example given previously, one of the strategies for searching for a target using a CCD camera is to rotate the robot once in the clockwise direction until the target is in the view of the CCD sensor. CAN message structure is as follows: (message identifier, (first module to implement control (what is to be controlled, what is to be done)), (second module to implement control(what is to be controlled, what is to be done)), …). If all the contents of the messages are the same, then the robot is controlled according the messages received and sent.

The bottom layer is the layer that controls and monitors the state of the actuators and sensors of the robot in order to achieve synchronised control of the robot. The lower layer is time critical, and is controlled by local microprocessor. In modular robot that contains two biped modules, clockwise rotation of the wall-climbing robot is achieved by moving the left legs to the front, one articulated leg a time (say Leg 1 and Leg 2), and moving the right legs to the back, one articulated leg at a time (say Leg 3 and Leg 4) (refer Figure 2). One sequence of leg movements to achieve this is (module1 (leg 1 (forwards)), module 2 (leg 1(forwards)), module 1(leg 2 (backwards), module 2(leg 2 (backwards))). When module 1 is finished moving Leg 1 forwards, it then sends a message on the CAN bus that Leg 1 has finished forward motion. Then module 2 starts moving its Leg 1forwards. When this has been finished, module 2 sends a CAN message that Leg 2 is finished moving forwards, and so on until the task has been finished. If an error is encountered while the leg is being moved e.g. pressure loss in he suction cups due to irregular surface, an error message regarding this task is sent on the CAN bus before the task is aborted and new control sequence has been generated.

7. CAN BUS MESSAGE DETERMINATION AND TASK SCHEDULING IMPLEMENTING FINITE STATE MACHINES

The determination of messages and their schedule in order to achieve synchronised and scheduled control of the wall-climbing robot is facilitated by using finite state machines technique. This technique is suited to modular systems which do not have more than 10 modules, or sub-systems of modular systems with more than 10 modules. The finite state machine consists of wall-climbing robot states (round rectangles in the Figure 7) combined by the transitions (arrows in the Figure 7) needed to achieve those states. The label on a transition has two parts separated by slash. The first is the name of the event that triggers the transition. The second is the name of an action to be performed once the transition has been triggered.

Figure 7 shows the state machines for three tasks: clockwise rotation, interrupt handling and leg error states. Only the clockwise rotation state has been elaborated. It consists of sub-states; robot still, rotate clockwise, rotate clockwise, rotate clockwise, rotate clockwise and repeat until loop finished. Each arrow that links the states indicates the CAN bus message which is required to achieve the following state. Clockwise rotation of the robot might be requested by the human user interface. The infra red sensors are used to determine if the robot’s leg has made contact with the surface or not. Pressure sensor indicating whether the surfaces contacted are good for vacuum suction or not is not shown i.e. indicating pressure losses or lack of vacuum pressure in the vacuum cups.

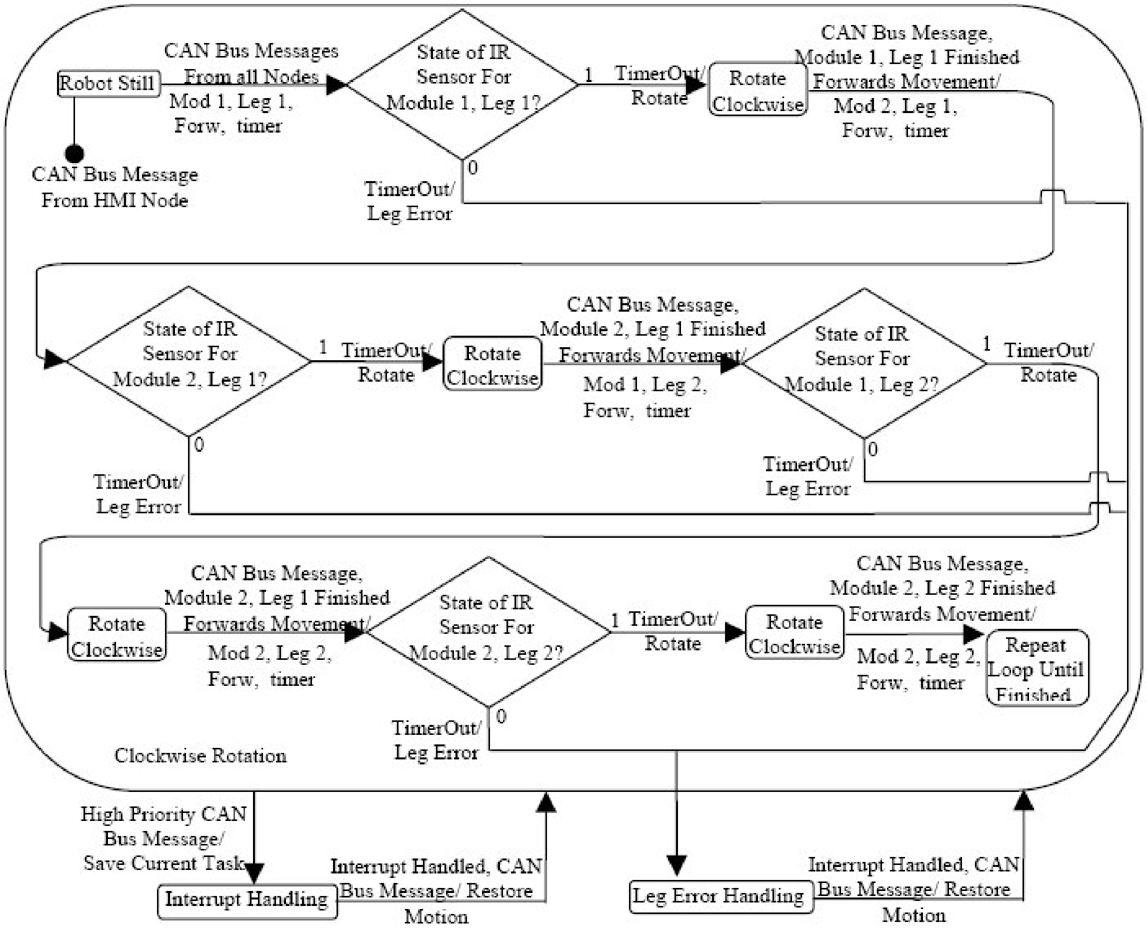


Figure 7. State Machine Diagram For Rotating Clockwise Initiated by Human-Machine Interface Node.

7 CONCLUSION

Biped robotic modules are designed. Assembly of a number of biped robotic modules in order to achieve modular wall-climbing robot is achieved by one DOF revolute joint between two consecutive modules. Since the connection between the consecutive modules is flexible, the developed wall-climbing robot can changes surfaces which are at an angle to each other safely e.g. moving from the floor to the wall.

The high number of sensors and actuators are used in the construction of the robot resulted in the use of CAN as a distributed mechatronics controller. CAN facilities adequate control of event based and time-critical tasks of the developed wall-climbing robot. CAN messages are divided into three hierarchal messages depending on the type of the message. The hierarchy also represents the priority of message on the CAN bus.

The maximum delay time for a CAN message can be calculated under normal circumstances only, for the message with highest priority (Wolfhard 1997). The delay times for the other messages cannot be calculated because of the bus access mechanism of the CAN i.e. Carrier Sense Multiple Access with Collision Detection and Arbitration on Message Priority (CSMA/CD +AMP). The delay time for a bus access to a message with highest priority is 130 bit times. CAN bit time is set to 16 T_Q (Section 5) with T_Q = 500 ns. Therefore the maximum delay for a message with highest priority is:

$$T_{\text{max\_delay}} = 130 * 16 * T_Q$$
$$= 1.04\ \mu\text{s}$$

Time-constants of the dynamics of the wall-climbing robot must not exceed this value if the CAN bus is to control the developed modular robot with stability. As the number of modules is increased, the time delay of critical messages will be increase as well. Finite state machines can be further used to reduce the number of message that are required, at the expense of some feedback control messages on CAN bus. Further improvements on the reduction of CAN bus messages used when the is a large number of modules can be done implementing a behaviour based approach to robot control. Under certain behaviours, certain messages are broadcast on the CAN bus.

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