A Low-Cost Easy-Operation Hexapod Walking Machine

Giuseppe Carbone and Marco Ceccarelli
Laboratory of Robotics and Mechatronics, DiMSAT, University of Cassino, Via Di Biasio 43, 03043 Cassino (Fr), Italy
Corresponding author e-mail: carbone@unicas.it

Abstract: *This paper presents the mechanical design of an hybrid hexapod walking machine that has been designed and built at LARM: Laboratory of Robotics and Mechatronics in Cassino. Basic characteristics are investigated in order to design a leg system with suitable low-cost modular components. Moreover, special care has been addressed in proposing an architecture that can be easily operated by a PLC with on-off logic. Experimental tests are reported in order to show feasibility and operational capability of proposed design.*
Keywords: *Walking Machines; Wheeled Leg, Low-Cost Design.*

1. Introduction

Since long times a challenge in robotics has been designing intelligent walking machines, which can move on uneven terrains and areas that are inaccessible to humans. Walking machines can help humans, for example in demining, pipe inspection, inspection and restoration of archeological sites, and interplanetary exploration as reported in (Berns 2007; Salmi & Halme 1996; Gonzalez de Santos et al. 1998; Horodinca et al. 2002; Zielinska & Heng 2002).
Walking machines can be of several different types. Most of them are equipped with biologically inspired legs. In fact, legged locomotion systems that have evolved in nature, show very good performances in terms of stability, payload capabilities, dynamic behavior, rough terrains operation, obstacle avoidance. Nevertheless, walking machines with biologically inspired legs can be slow and more difficult to design and operate with respect to machines that use wheels or crawlers. Thus, hybrid walking machines have been proposed in order to overcome the drawbacks and get the advantages of both biologically inspired legs and wheels or crawlers.
In this paper, a design of a hexapod hybrid walking machine is proposed. This hexapod walking machine is composed of six legs having a modular anthropomorphic architecture with a wheel as foot at its extremity. Main features in the mechanical design of the legs have been modularity and low-cost. Moreover, a design constraint has been a easy operation within an on-off environment by means of a commercial PLC (Programmable Logic Controller), and by using proper mechanical limit switches. This type of operation strategy has been already successfully tested on other prototypes at LARM as reported for example in (LARM webpage 2007).

2. The mechanical design and hardware

The proposed design has been conceived for developing a walking leg by using mainly low-cost industrial components with the following basic requirements:

- to have a robust simple mechanical design;
- to have a modular design that can be used for robots with different number of legs;
- to be operated with an easy flexible programming;
- to have low-cost both in design and operation.

Those requirements can be achieved in a very practical way by using low-cost components from the market into a suitable design for the whole system. In particular, Fig 1 reports main components that have been selected and used for assembling a robotic leg having three degrees of freedom (dofs). This assembly solution has been designed as based on previous experiences that are reported in (Carbone & Ceccarelli 2004; Carbone et al. 2005; Cigola et al. 2005; Shrot 2006). It is worth noting that the leg is composed of three modules made of commercial aluminium bars having hollow square cross-section shape. Each module contains a commercial DC motor, two toothed pulleys, a timing belt, two limit switches for the extreme reaches and a hinge pin in order to connect the module to another one.
Additional components are needed for the extremity modules. In particular, the support module requires an additional fixing part, and the module for wheel requires an additional wheel. Figure 1a) shows a built prototype of the proposed leg. It has a total height of 0.5 m and a weight of about 25 N and its maximum step size is of 155mm. It is worth noting that legs having more dofs can be assembled by adding more modules.
The above-mentioned modular design of one leg in Fig.1a) has been used has basic component for a hexapod

hybrid walking machine. In particular, six legs have been connected to a suitable body in order to build the prototype that is shown in Fig.2. This walking machine can fit into a cube of 0.6m x 0.6m x 0.5m and it has an overall weight of 180N. It can carry on-board its own control board (including a commercial PLC). In this case, the robot weight is 22 N. Expected field of application for this prototype can be the inspection and operation in nonaccessible sites as outlined in (Cigola et al. 2005).

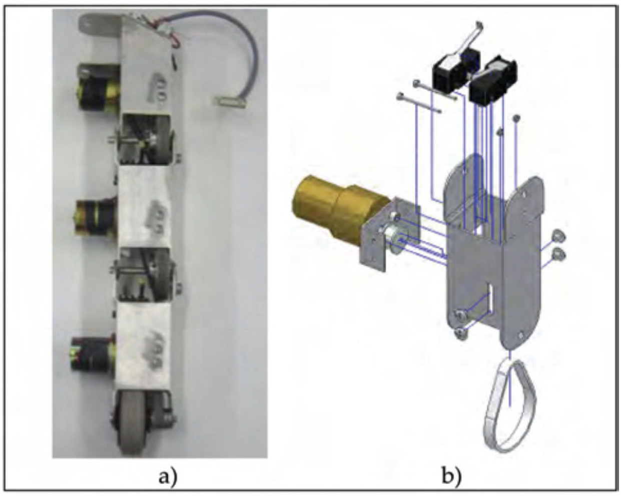

Fig. 1. A built leg prototype having three dofs: a) front view; b) exploded view of one module

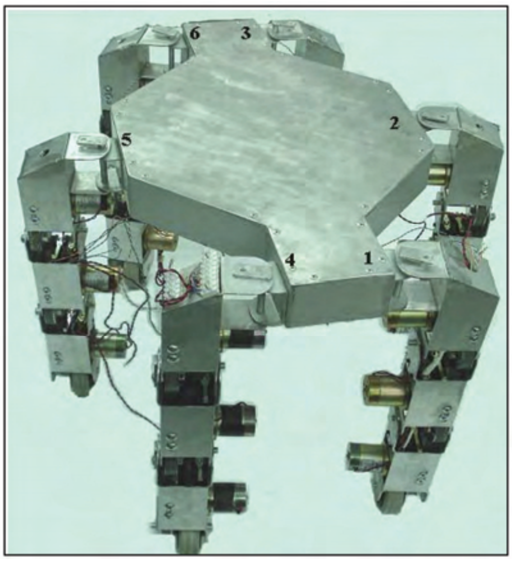

Fig. 2. The prototype of Cassino Hexapod that has been designed and built at LARM in Cassino

3. Operation capability

The operation of Cassino Hexapod walking machine is achieved by means of the set-up whose scheme is reported in Fig.3. In particular, this hexapod walking machine is composed of six legs each having on board three DC motors. Thus, a total of 18 DC motors are controlled for the operation of this walking machine. A commercial PLC Siemens S7-200 series has been chosen as main control unit together with additional I/O boards.

The PLC is connected to a PC by means of a standard RS 232/PPI Cable. Off□line programming can be achieved on the PC by means of the commercial software Siemens STEP-7/Micro WIN 32. Then, the program can be easily downloaded on the PLC flash memory and the cable can be disconnected. A commercial DC power source provides the power supply for both the PLC and DC motors. A simple control pad with latching switches is used for operating the hexapod and for emergency stop.

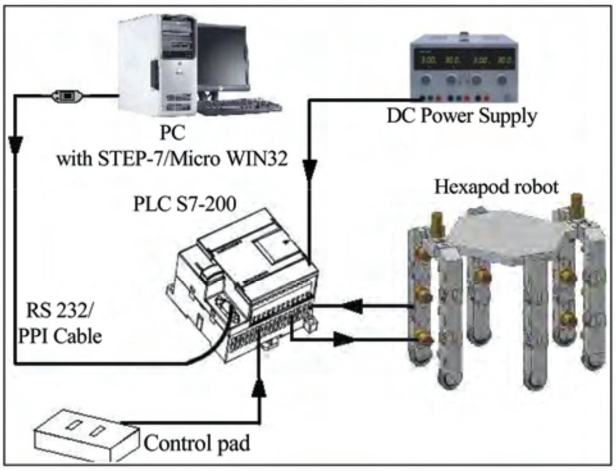

Fig. 3. Schematic diagram showing the hardware layout.A uniform way of naming the motors has been adopted. The motors are named as x.y, where x refers to the leg number on the hexapod (see Fig. 2) and y refers to the motor number

The motor of any leg is numbered from top to bottom. It should be noted that the motors of the right side and the left side of the robot are connected with opposite polarity. This is done to ensure that the control of both the halves of the robot are identical. In fact, due to the axialsymmetry a motor rotating in clockwise direction for the left side of the hexapod produces the same motion effect of a motor that is rotating in counterclockwise direction on the right side.

It is worth noting that each wheel is operated independently by one DC motor. But, in a preliminary system the motors of the wheels on the left side (legs 1-2-3) are connected together. Likewise, the motors of the wheels on the left side (legs 4-5-6) are connected together. This solution reduces the number of necessary I/O ports. Moreover, it simplifies the operation strategy of wheels for forward, backward and turning motions. In fact, forward and backward motions can be achieved when all the wheels move at same speed in the same clockwise or counterclockwise direction, respectively. Instead, the turning operation can be achieved by operating the wheels of left side and right side in opposite directions.

The selection of operation type can be obtained thourgh the control pad by selecting proper latching switches combination. In particular, the control pad has five latching switches that have been named progressively from S1 to S5 with S1 being the emergency stop.

A hexapod consists of six legs and proper movement of the robot is possible by properly synchronizing the motion of all the legs. Thus, programming the movement of one leg is very important for the successful movement of the robot. Various operation strategies have been analyzed and implemented on the built prototype. In particular, Grafcet analysis of a forward walking of one leg, continuous forward walking, and wheel operation of the whole hexapod robot are reported in Figs.4 to 6. It is worth noting that Grafcet is a graphic method of functional analysis which represents the functions of a sequential automated system as a sequence of steps and transitions. Each step represents a command or action that is either active or inactive (1 or 0).

The flow of control passes from one step to the next through a conditional transition that is either true or false (1 or 0). If the transition condition is true, control passes from the first step, which becomes inactive, to the next step, which then becomes active, and so on. Each control function, at any level, can therefore be represented by a group of steps and transitions, called a function chart. These charts can then be interconnected in the required sequence, by directed lines showing the flow of control, so as to form a complete Grafcet chart. In Grafcet diagram, each step is represented by a numbered square. The actions associated with the steps are described inside one or more rectangles to the right of the step. Transitions are represented by short horizontal lines. Conditions associated with the transitions may be written to the right of the transition.

In Figs. 4 and 5 descriptive and functional Grafcet diagrams are reported for the forward and backward operations of one leg. This operation strategy for one leg is the basic operation strategy that will be used in executing other complex motion tasks. Motors in each leg of the robot have been named as M_1, M_2 and M_3 and their counterclockwise motion is taken as positive. Also the limit switches have been numbered accordingly. Then, in the control pad, switch S1 acts as a master power source. No power supply reaches the hexapod robot unless it is switched on. Switch S2 is used for forward motion of the leg. When S2 is switched on, motor M_1 moves in counterclockwise direction and M_2 moves in clockwise direction. The motion of the leg stops when the limit switches 2 and 3 are clicked on.

Figure 6 shows the Grafcet diagram for a forward walking operation of the hexapod robot. In this forward walking operation strategy a tripod gait has been considered as reported in the scheme of Fig.7. In fact, for maintaining the stability of the robot, at least three legs should be in contact with the ground simultaneously. In a tripod gait, the front and rear leg of one side and the middle leg of another side perform their swing movements at the same time. A delay is introduced between each step in order to ensure proper coordination and phase difference among the motion of legs. This delay was chosen after experimental tests and is also a function of the power supply voltage. The operation of each leg has the same logic that is reported in the Grafcet diagram of Fig.4.

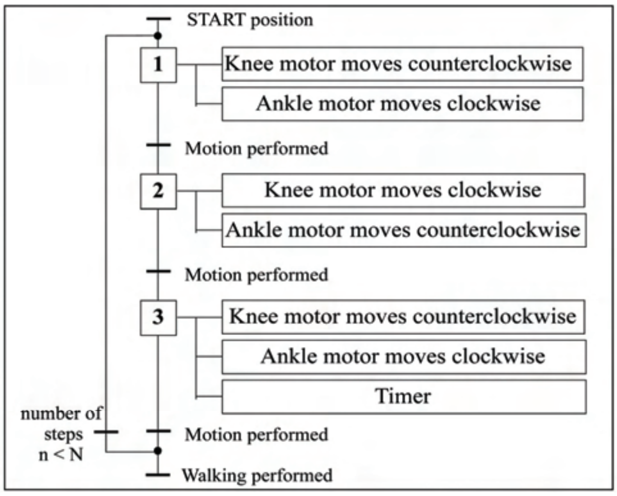

Fig. 4. Descriptive Grafcet of forward and backward motion of one leg

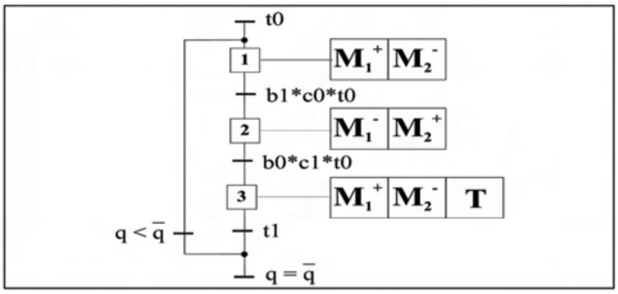

Fig. 5. Functional Grafcet of forward and backward motion of a leg

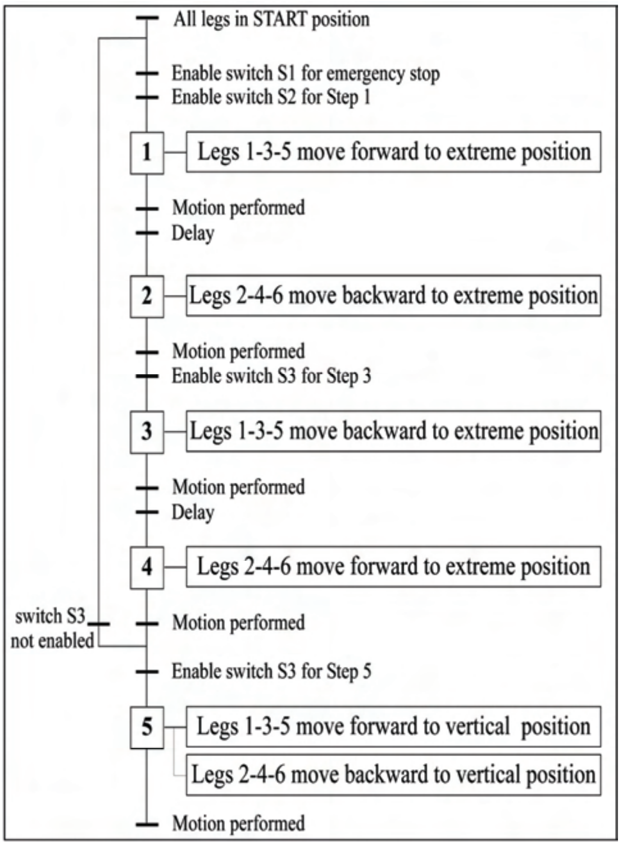

Fig. 6. Descriptive Grafcet for forward walking operation of the hexapod

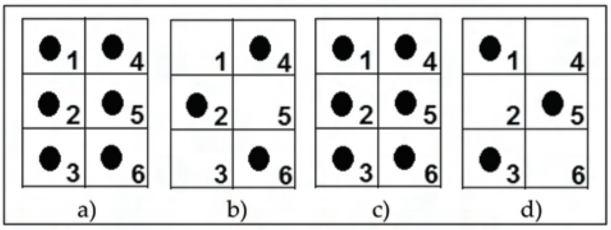

Fig. 7. Scheme of tripod gait for Cassino hexapod: a) all legs are in contact with ground; b) legs 1-3-5 are lifted and moved forward; c) all legs come in contact with ground; d) legs 2-4-6 are lifted and moved forward

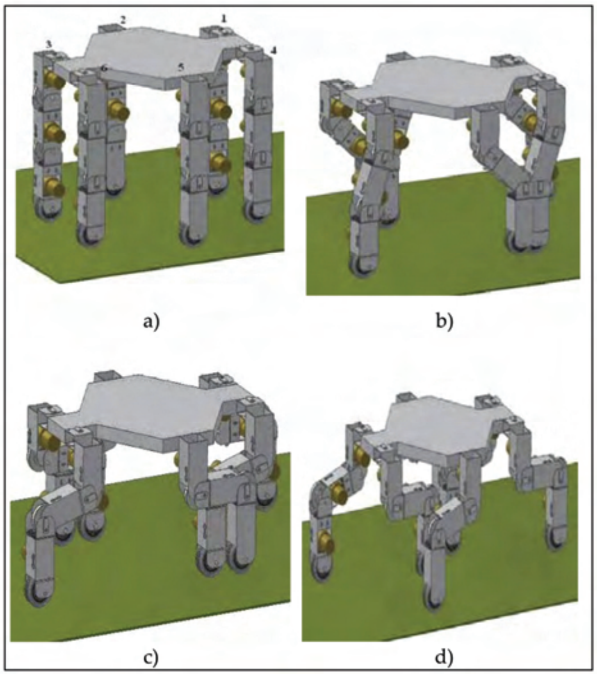

Fig. 8. Phases for a one step double tripod forward walking motion of a hexapod robot according to the Grafcet diagram in Fig.6: a) initial configuration; b) 3 legs move forward; c) 3 legs reach the maximum forward configuration and the other 3 start moving backward; d) final configuration

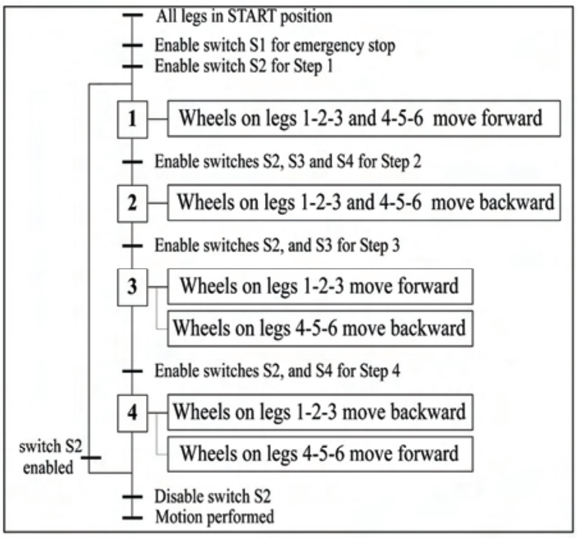

Fig. 9. Descriptive Grafcet for wheel operation of the hexapod robot; forward, backward and turning operations are achieved by selecting a proper combination of latching switches S3 and S4

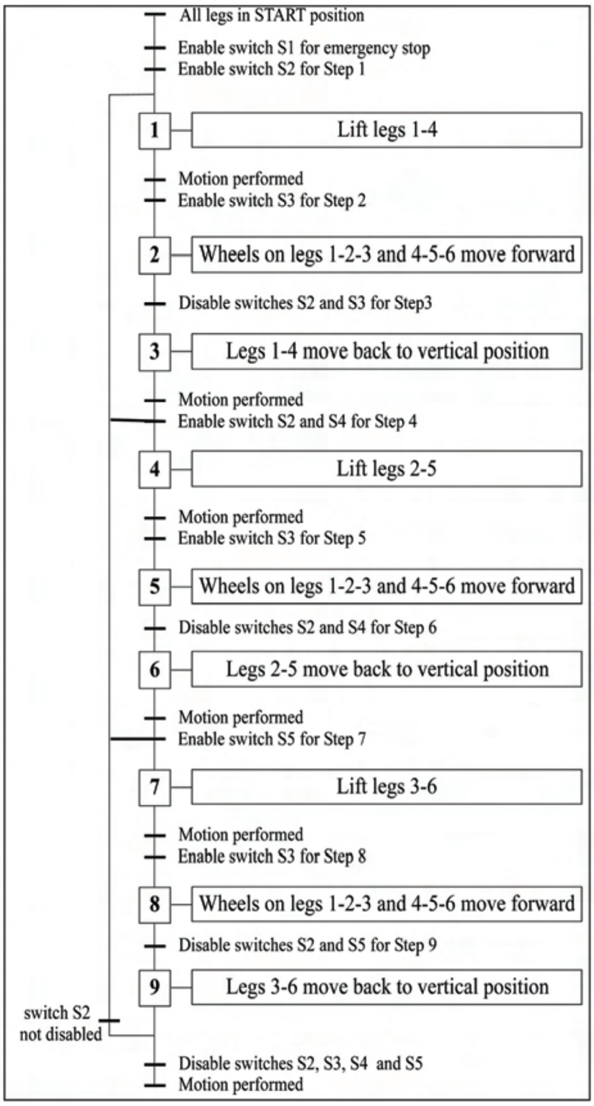

Fig. 10. Descriptive Grafcet for obstacle avoidance operation

4. Experimental tests

Several experimental tests have been carried out on the built prototype of Cassino hexapod. In particular, Fig.11 shows some of the configurations during a leg operation by implementing the Grafcet of Figs. 4 and 5. It is worth noting that one step forward motion is completed in less then 10 sec. when the input tension is 12 volts. The same motion requires about 5 sec. if the input tension is 24 volts. Thus, the operation speed of each leg and also of the whole hexapod can be easily regulated by modifying the input tension of the actuators from 12 to 24 volts.
Figure 12 shows a sequence of images for the forward walking operation of Cassino hexapod according to the Grafcet logic of Fig.6. The tripod gaits are achieved by using the same operation strategy and speed of Fig.11 with proper synchronization among the legs.
Figure 13 shows the wheel operation of the hexapod robot according to the Grafcet of Fig.9. In this experiment the robot moves forward at a speed of about 0.3 m/s and then turns right of 90 deg.

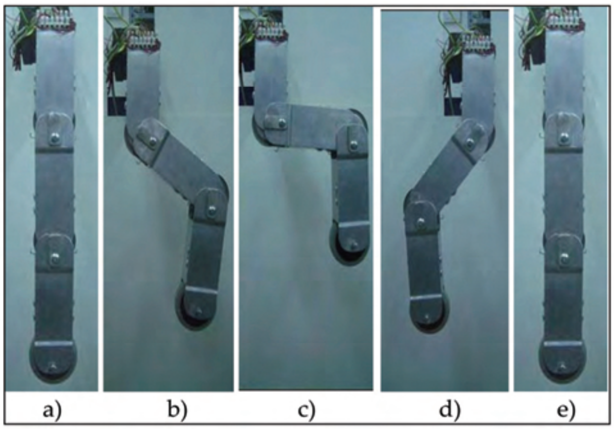

Fig. 11. Sequence of images showing a forward and backward motion test for one leg according to the Grafcet of Figs.4 and 5: a) initial straight leg configuration; b) intermediate forward configuration; c) maximum forward configuration; d) intermediate backward configuration; e) final straight leg configuration

5. Conclusions

The mechanical design of an hybrid hexapod walking machine is presented as based on a modular anthropomorphic wheeled leg design. These leg modules have been designed and built mainly by using low-cost commercial components. Also the operation strategies have been proposed and implemented as based on a commercial PLC unit with on-off logic. A first prototype has been built and it has been preliminarily experienced with satisfactory results regarding with motion capability and easiness of motion programming and operation.

Kinematic simulations of the proposed operation strategies have been performed in Autodesk Inventor environment as reported, for example in Fig.8. In particular, the simulation of Fig.8 refers to the Grafcet logic of Fig.6. Further details on the simulation process including other simulation conditions and a proper dynamic model for the proposed leg are available in previous works of the authors (Carbone & Ceccarelli 2004; Carbone et al. 2005; Cigola et al. 2005; Shrot 2006).

A Hybrid robot like the Cassino Hexapod can also use wheels for locomotion on flat ground. This way robot can move fast without consuming a lot of energy. Differential turning of the wheels can be used in order to turn the robot in right or left direction. The Grafcet logic for this operation has been presented in Fig.9. Moreover, the operation of legs and wheels can be combined for obstacles avoidance purposes as proposed, for example in the Grafcet diagram of Fig.10. In particular, if an obstacle is detected the neighborhood two legs can be lifted up. Then, the hexapod robot can move forward by means of the wheels. The two legs can go back to the straight configuration and afterwards other two legs can be lifted up. This procedure can continue until the robot overcomes the obstacle(s).

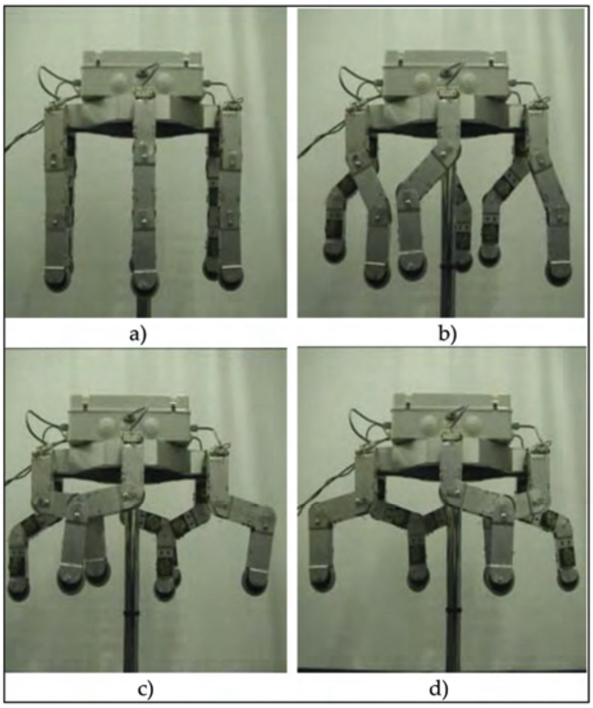

Fig. 12. Sequence of images showing a forward walking test of Cassino hexapod on a fixed base: a) initial straight leg configurations; b) 1-3-5 legs in intermediate forward configuration and 2-4-6 legs in intermediate backward configuration; c) 1-3-5 legs in forward configuration and 2-4-6 legs in backward configuration; d) 2-4-6 legs in forward configuration and 1-3-5 legs in backward configuration

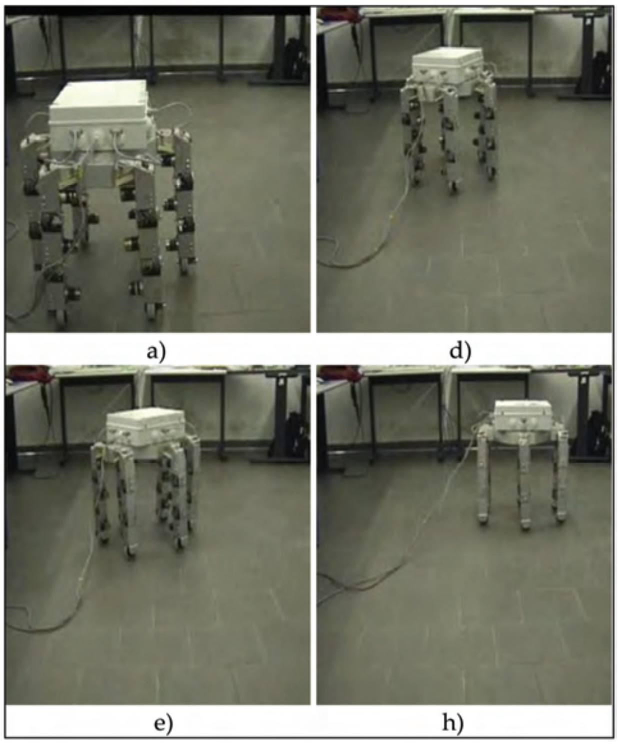

Fig. 13. Sequence of images showing a wheel operation test of Cassino hexapod: a) initial position; b) second turning position (30 deg.); c) forth turning position with forward motion (60 deg.); d) final position (90 deg.)

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