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EP-WAR3 biped robot for climbing and descending stairs

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SUMMARY
A biped walking robot, named EP-WAR3 (Electro-Pneumatic-Walking-Robot), has been designed, built and tested at LARM (Laboratory of Robotics and Mechatronics) in Cassino. EP-WAR3 is provided with a suitable binary pneumatic actuation in order to be controlled through a common PLC (Programmable-Logic-Controller) as an event-based system in an on/off environment. The walking stability of the biped robot is obtained by using suction-cups, which are installed on the underside of each foot. EP-WAR3 is able to walk along a straight line with two different step sizes, turn right and left, and to climb and to descend stairs. A suitable motion analysis and programming technique of the PLC controller is proposed in order to obtain suitable walking capabilities and flexibility of the robot.

KEYWORDS: Biped robot; Walking stability; Climbing and descending stairs.

1. INTRODUCTION

The design and control of biped robots is a very complex task, but they have a better capability of adapting to unstructured environment than other kinds of mobile and walking robots. Thus, several researches are in progress to design biped robot prototypes with suitable performances. Some of the most known biped robots are illustrated in references [1–8]. The prototypes WABIAN[1,2], Honda[3], BIP2000[4,5], Johnnie[6], and Curbi[7] have been designed for performing static and dynamic walking in several environments.

A specific research has been carried out at LARM in Cassino, in order to obtain a low-cost biped robot prototype, which is able to move autonomously in structured environments, like industrial plants. This paper deals with a third version of the biped robot prototype, which is named as EP-WAR3 (Electro-Pneumatic-Walking-Robot). The first prototype EP-WAR was able to walk straight, to turn right and left, as described in reference [9]. The second prototype EP-WAR2 was also able to climb stairs[10,11]. Then, EP-WAR3 has been designed, built and tested at LARM in order to descend stairs too, as presented with preliminary results in references [12] and [13]. After a description of the leg mechanism and its actuation system, a specific programming technique of the PLC (Programmable-Logic-Controller) is designed in order to confer straight walking, turning on the right and left sides, and climbing and descending stairs. Finally, successful experimental tests at LARM have validated the performances of EP-WAR3.

2. MECHANICAL DESIGN OF THE EP-WAR3 BIPED ROBOT

A pantograph and a double articulated parallelogram compose the leg mechanism of the EP-WAR3 robot prototype, as shown in Fig. 1.

The pantograph *ABCGHN* transmits the motion from the actuation point H to the ankle point C through a scale factor equal to 4, because of the mechanism size, that is reported in Table I. This linkage gives a proper mechanical design to install the actuation system on the robot body, and an anthropomorphic design can be obtained for suitable walking capabilities.

The double articulated parallelogram *ABCDEF* gives a pure translation of the foot in a vertical plane as required by two suction-cups, which are installed on the underside of each foot. These suction-cups ensure the equilibrium of the biped robot for walking and turning on smooth floors, climbing and descending stairs.

Referring to Fig. 1a, two d.o.f.s (degrees of freedom) of each leg mechanism are actuated by five double-acting pneumatic cylinders. In particular, cylinders $\mathcal{A}$ and $\mathcal{B}$ are connected in series in order to obtain a unique linear actuator, which can give four positions because of their digital operation. This linear actuator is installed on the robot body through the revolute joint A. Similarly, cylinders $\mathcal{C}$ and $\mathcal{D}$ are installed in an opposite position on the robot body through the revolute joint Ω. Both the assembled linear actuators, which are composed by cylinders $\mathcal{A}$ and $\mathcal{B}$, $\mathcal{C}$ and $\mathcal{D}$, respectively, are connected to the actuation point H of the right leg mechanism. Thus, taking into account that cylinders $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$ and $\mathcal{D}$ are operated as binary actuators in an on/off environment, sixteen theoretical positions of H can be obtained in a vertical plane of the leg mechanism. In fact, one has $2^4 = 16$, where number 2 corresponds to the possible binary configurations for each cylinder piston and 4 is the number of cylinders. But only fifteen of these sixteen configurations are possible for the pantograph leg mechanism because of mechanical constraints. Referring to Table I, these configurations can be described in the absolute motion with respect to the terrain, to give a short step with size $p_s = 320$ mm, a long step with size $p_l = 800$ mm and to climb stairs.

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Table 1. Sizes and characteristic of the built prototype of Fig. 1.

Leg mechanism [mm]						Absolute step sizes [mm]			
AB	*BC*	*HG*	*NH*	*AC*	*BE*	p_s		p_l	
300	400	75	225	660	120	320		800	
Cylinders			$\mathcal{A}, \mathcal{E}$		$\mathcal{B}, \mathcal{F}$	$\mathcal{C}, \mathcal{G}$	$\mathcal{D}, \mathcal{H}$	$\mathcal{M}, \mathcal{N}$	$\mathcal{I}, \mathcal{L}$
bore [mm]			80		80	50	50	10	25
stroke [mm]			30		45	70	30	40	30°
Ejectors/Suction-cups			$\mathcal{O}, \mathcal{P}$						
size			3/8				----		
diameter [mm]			----				125		

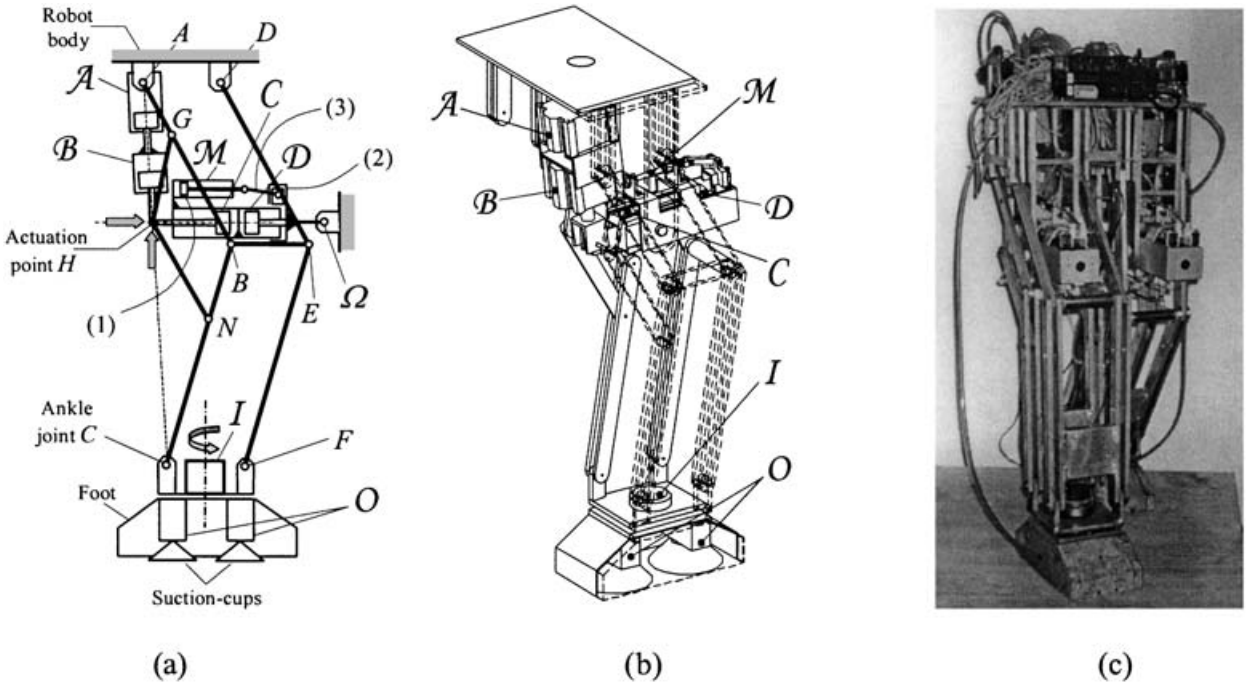


Fig. 1. EP-WAR3 (Electro-Pneumatic-WAlking-Robot): (a) leg mechanism and its actuation system; (b) a 3-dimensional view of the right leg; (c) robot prototype.

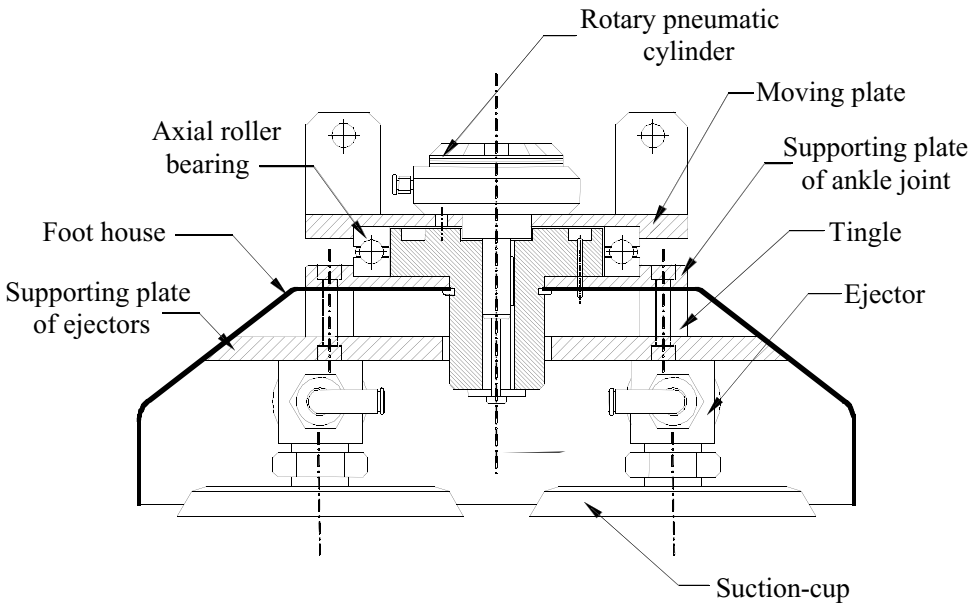


Fig. 2. A cross-section of the mechanical design for the foot of the EP-WAR3 biped robot.

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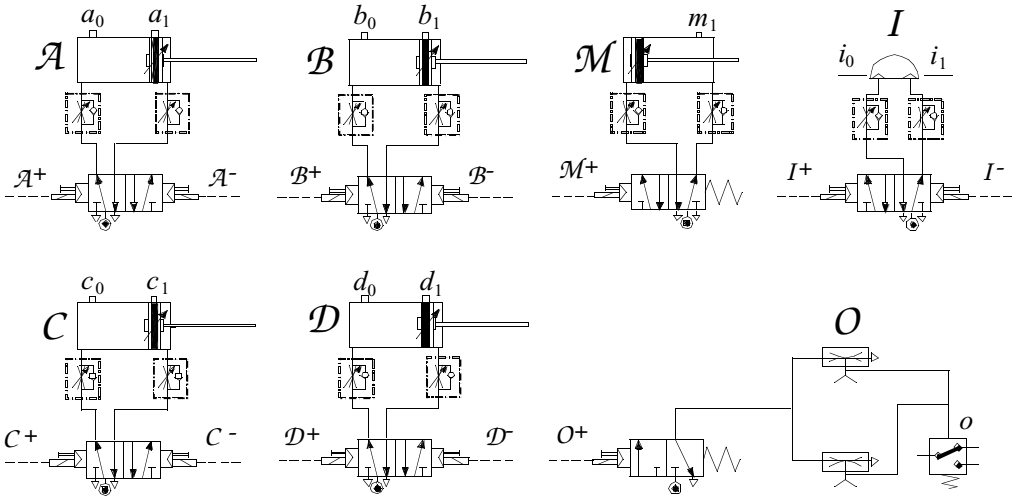


Fig. 3. Electro-pneumatic circuit for the right leg of the EP-WAR3 at a starting configuration to perform a straight long step.

In addition, a suitable ankle joint for each leg mechanism allows the relative rotation about the vertical axis across the center of the foot. This third d.o.f. of each leg mechanism is actuated by a double-acting rotary pneumatic cylinder, which is indicated by I for the right leg. A rotation of $\beta = 30$ deg is possible in order to turn the robot on the right and left sides. The mechanical design of the foot has been conceived to ensure the walking stability of EP-WAR3, as shown in Fig. 2. The suction-cups can work in suitable way only when the foot is moved according to a pure translation in the vertical plane. In fact, it is necessary to push the foot house on a flat terrain in order to obtain a bilateral constraint between foot and ground. These performances have been obtained through a suitable design of the foot and leg mechanism of the robot. In fact, the ankle joint has been designed by using an axial roller bearing, which has been installed between a moving plate connected to the leg mechanism, and the supporting plate installed on the foot house.

Moreover, two additional positions for the linear actuator that is composed by cylinders $\mathcal{C}$ and $\mathcal{D}$, are required to obtain additional configurations of the leg mechanism in order to descend stairs with a suitable foot position on the step plate. These positions have been obtained by limiting the stroke of the cylinder $\mathcal{D}$ by means of a suitable slider of 7.3 mm, which is actuated by the pneumatic cylinder $\mathcal{M}$ through a Cardan mechanism, as shown in Figs. 1a and 1b. Prismatic pairs of the Cardan mechanism correspond to the piston-tube (1) of $\mathcal{M}$ and slider-slot (2). The outstroke motion of the cylinder $\mathcal{M}$ moves the slider (2) through the coupler (3). Thus, the stroke of the cylinder $\mathcal{D}$ can be limited in a required position, in order to obtain a unique linear actuator composed by $\mathcal{C}$ and $\mathcal{D}$, which can give six different positions with this additional slider. The system allows to descend stairs of standard step sizes with tread of 300 mm and riser equal to 160 mm.

Referring to Fig. 3, the five double-acting pneumatic cylinders $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$ and I are operated by five 5/2 (five-way/two-position) solenoid-solenoid valves, respectively, and cylinder $\mathcal{M}$ is actuated by a 5/2 spring-solenoid valve. Twelve check-choke valves allow the manual speed regulation of each cylinder and a 3/2 (three-way/two-position) spring-solenoid valve operates the ejectors O of the suction-cups.

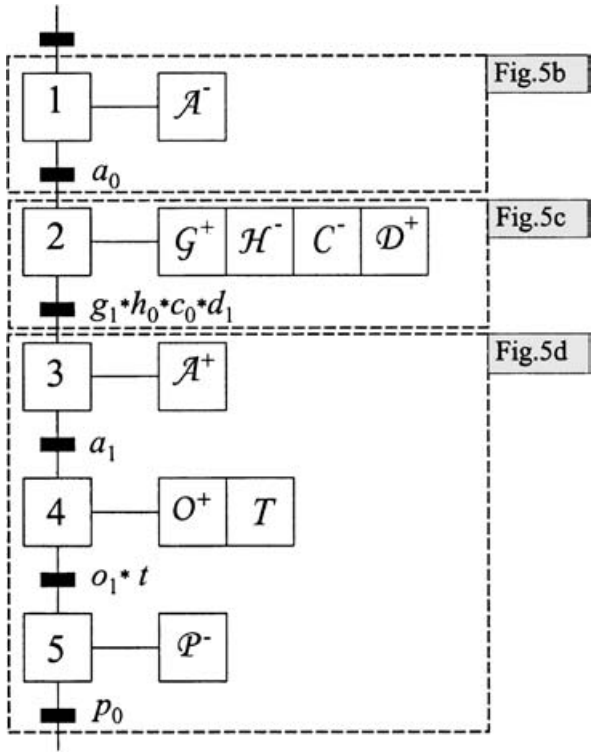


Fig. 4. Grafcet diagram for a short right half-step.

3. MOTION ANALYSIS OF THE STRAIGHT WALKING

The proposed binary pneumatic actuation of EP-WAR3 biped robot is controlled as an event-based system in an on/off environment. A common PLC has been used and a suitable programming technique is designed in order to obtain a suitable flexibility of the robot for walking and turning on smooth floors, climbing and descending stairs. It is worth

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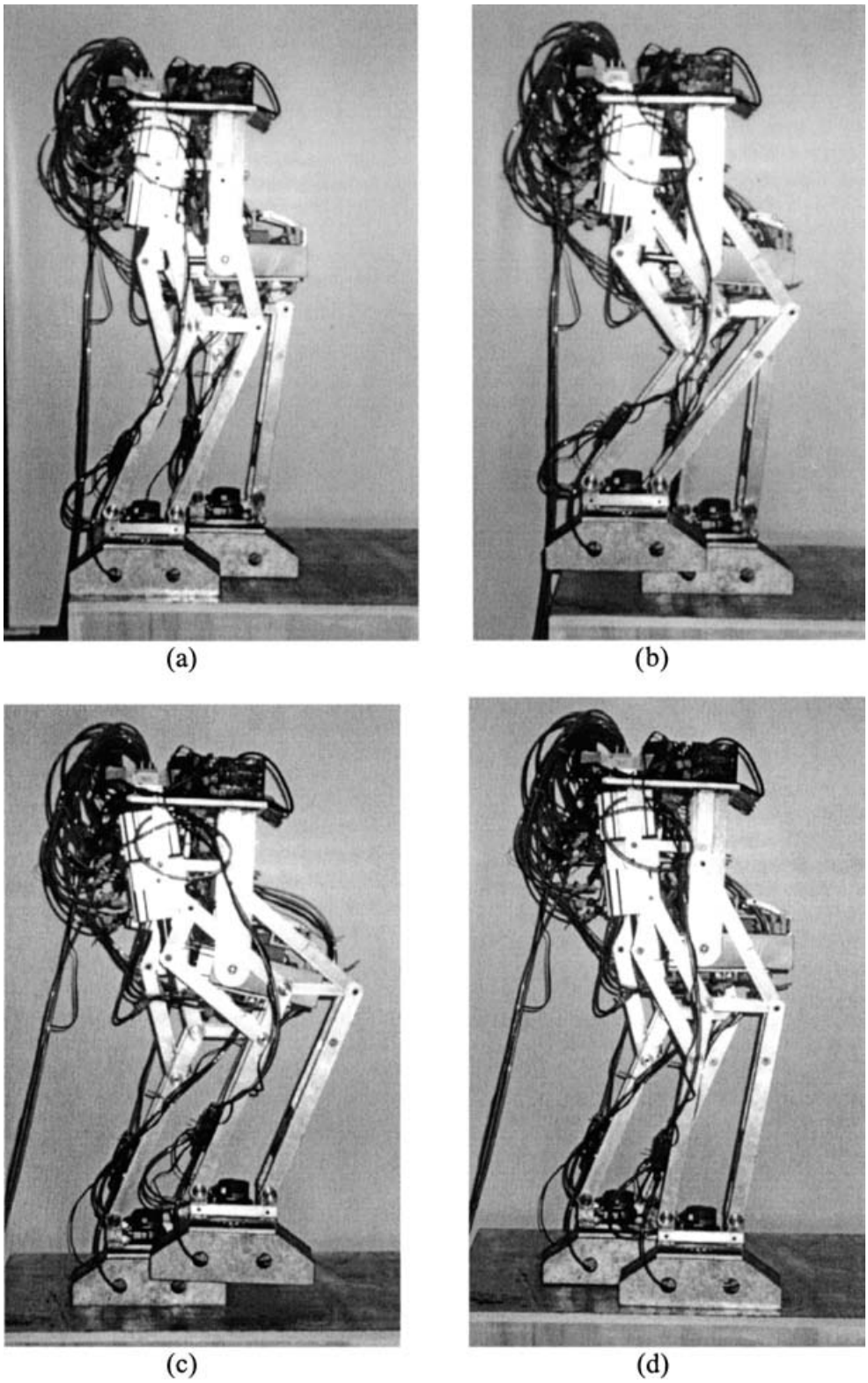


Fig. 5. Experimental test at LARM (Laboratory of Robotics and Mechatronics) with the EP-WAR3 robot prototype performing a short right half-step in the absolute motion with respect to the smooth floor, according to the Grafcet diagram of Fig. 4: (a) starting configuration; (b) right foot is lifted; (c) right foot and robot body are moved forward; (d) right foot is put onto the floor.

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noting that any robot trajectory can be decomposed into a certain number of basic modular trajectories: straight paths for walking straight, and polygonal paths for turning on the right and left side. Moreover, suitable basic modular trajectories of the robot can be conceived in order to climb and descend stairs.

Similarly, each basic trajectory can be obtained through a sequence of elementary actions, which can be performed by the on/off actuation system. Thus, a suitable subroutine can be properly programmed for each basic trajectory and using a Main Program, which calls these subroutines suitably, several trajectories of the robot can be performed. The inputs of the Main Program consist of different kinds of half-step and the choice of the walking motion is carried out by changing the Main Program without modifying the subroutines. The PLC controller has been programmed by using the Ladder Diagram, as for the most common electro-pneumatic systems of industrial environments.

The motion analysis of the straight walking of EP-WAR3 biped robot with a short right half-step can be carried out referring to the Grafcet (GRAphe Fonctionnel de Commande Etapes-Transitions) diagram of Fig. 4 and Fig. 5. This means that only right foot is moved forward and the step size with respect to the robot body is equal to 160 mm, which corresponds to a step size of 320 mm in the absolute motion. Of course, a next left half-step forwards the robot body of 320 mm. In particular, starting by the robot configuration of Fig. 5a with the left foot ahead and attached to the floor because of its suction-cups, the right foot is lifted by the control signal $\mathcal{A}^-$ and reaches the configuration of Fig. 5b. Then, the right foot is moved ahead, while the left foot is moved back and, consequentially, the robot body is moved ahead since the left foot is attached to the floor by its suction-cups. This phase of the Grafcet of Fig. 4 is obtained through the control signals $\mathcal{G}^+$, $\mathcal{H}^-$, $\mathcal{C}^-$ and $\mathcal{D}^+$, which give the robot configuration of Fig. 5c. Finally, the right foot is put on the floor through the signal $\mathcal{A}^+$, and the right foot becomes the supporting foot instead of the left foot, because of the signals O^+, $\mathcal{P}^-$ and t of the timer T. Therefore, EP-WAR3 is ready to perform a short left half-step in order to move the robot body of 320 mm.

Similarly, the motion analysis of the straight walking of EP-WAR3 with a long right half-step can be carried out by referring to the Grafcet diagram of Fig. 6. This sequence of movements is very similar to that related with the Grafcet of Fig. 4, but the second phase is different in order to perform a different step size. In fact, the control signals $\mathcal{G}^+$ and $\mathcal{H}^+$ move fully back the left foot that is attached to the floor, while $\mathcal{C}^-$ and $\mathcal{D}^-$ move fully ahead the right foot by giving a step size of 800 mm and a forward displacement of the robot body equal to 400 mm. On the other hand, the control signal $\mathcal{G}^+$ moves back the left foot partially, and $\mathcal{C}^-$ moves ahead the right foot partially in order to perform a short step of 320 mm, as shown in Figures 4, 5b and 5c.

4. MOTION ANALYSIS FOR TURNING RIGHT AND LEFT

The Grafcet diagram of Fig. 8 shows the elementary actions of EP-WAR3 in order to turn on the right side. In the first

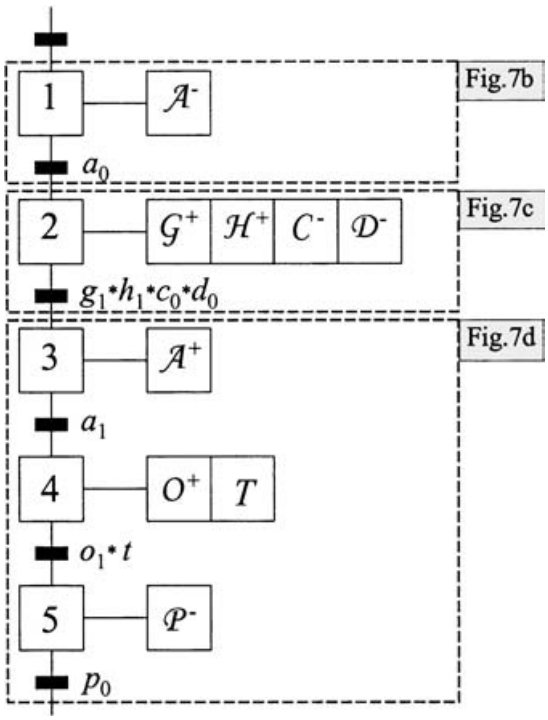


Fig. 6. Grafcet diagram for a long right half-step.

phase, the control signal $\mathcal{E}^-$ pulls upward the left foot as shown in the experimental test of Fig. 9a and in the second phase the robot turns right about the vertical axis through the right foot because of the signal I^+ that actuates the rotative cylinder I. Thus, the robot configuration of Fig. 9b is reached and the signal $\mathcal{E}^+$ is activated to position left foot on the floor, as depicted in Fig. 9c. Then, the right foot has to be aligned with the left foot in order to complete the rotation of the robot and this is performed through the phases 4 to 9 of the Grafcet diagram of Fig. 8. In particular, the left foot becomes the supporting foot instead of the right foot because of signals $\mathcal{P}^+$ and O^- and after the time t of timer T. This allows the lifting of the right foot because of the signal $\mathcal{A}^-$ in order to reach the configuration of Fig. 9d. Thus, signal I^- actuates the rotative cylinder I to align the right foot, which is put on the floor, as shown in Figs. 9e and 9f, respectively. Finally, the right foot becomes the supporting foot instead of the left foot because of the signals O^+ and $\mathcal{P}^-$, and after the time t of the timer T. Other steps can be performed. The switching of sensors e_0, i_1, e_1, p_1, o_0, a_0, i_0, o_1, p_0 and the end of time t allow the transition between the nine phases of the Grafcet of Fig. 8. Therefore, EP-WAR3 is rotated on the right side of 30 deg.

Similarly, the Grafcet diagram of Fig. 10 shows the elementary actions of EP-WAR3 in order to turn on the left side. The control signal $\mathcal{A}^-$ pulls upward the right foot, as shown in Fig. 11a, in order to give the turning of the robot about the left foot because of the signal $\mathcal{L}^+$ and thus the configuration of Fig. 11b is achieved. The right foot is put on the floor in Fig. 11c and, in sequence the left foot is lifted rotated and put on the floor, as shown in Figs. 11d, and 11f, respectively. Finally, the left foot becomes the supporting foot after the time t of the timer T and because of

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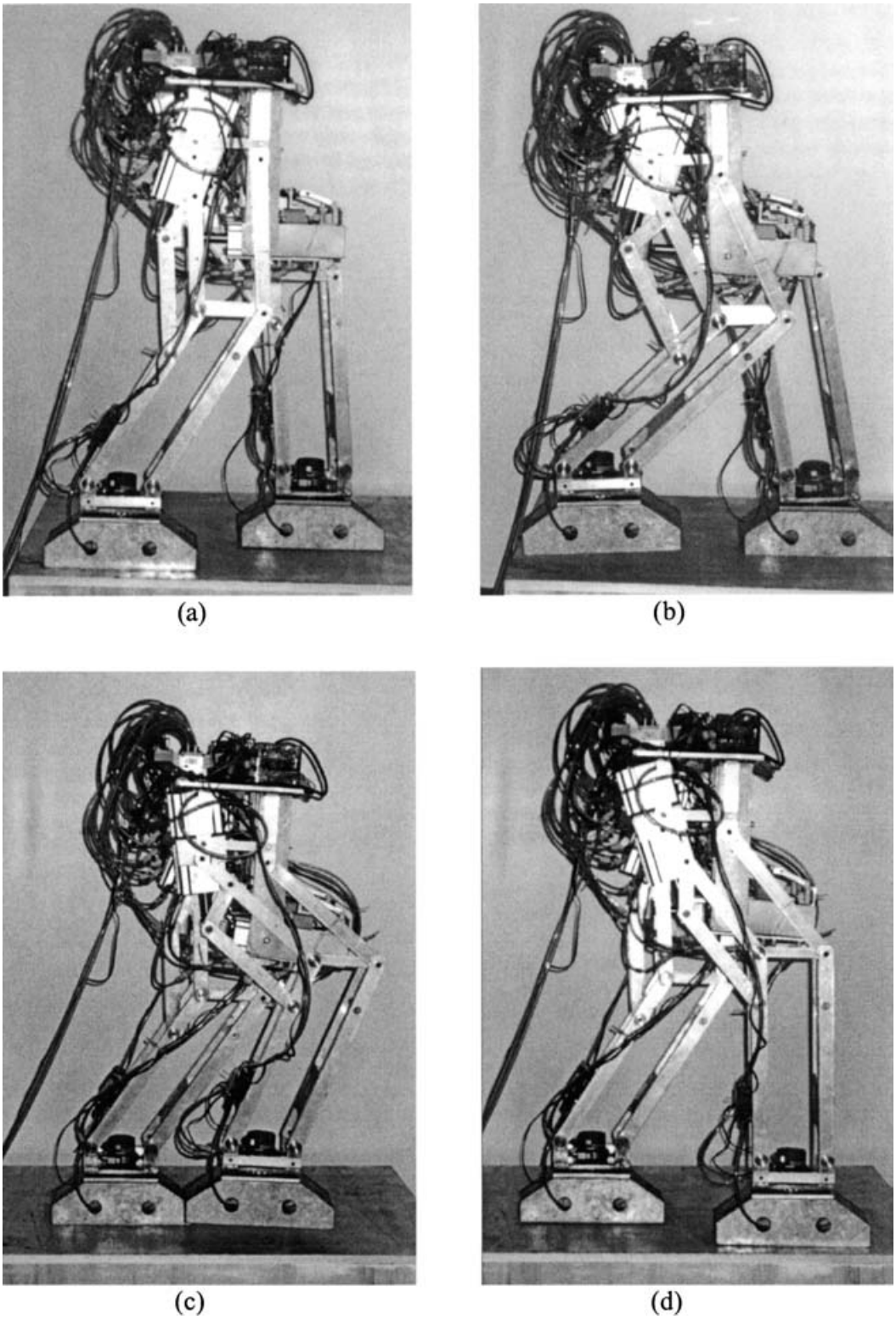


Fig. 7. Experimental test at LARM (Laboratory of Robotics and Mechatronics) with the EP-WAR3 robot prototype performing a long right half-step in the absolute motion with respect to the smooth floor, according to the Grafcet diagram of Fig. 6: (a) starting configuration; (b) right foot is lifted; (c) right foot and robot body are moved forward; (d) right foot is put onto the floor.

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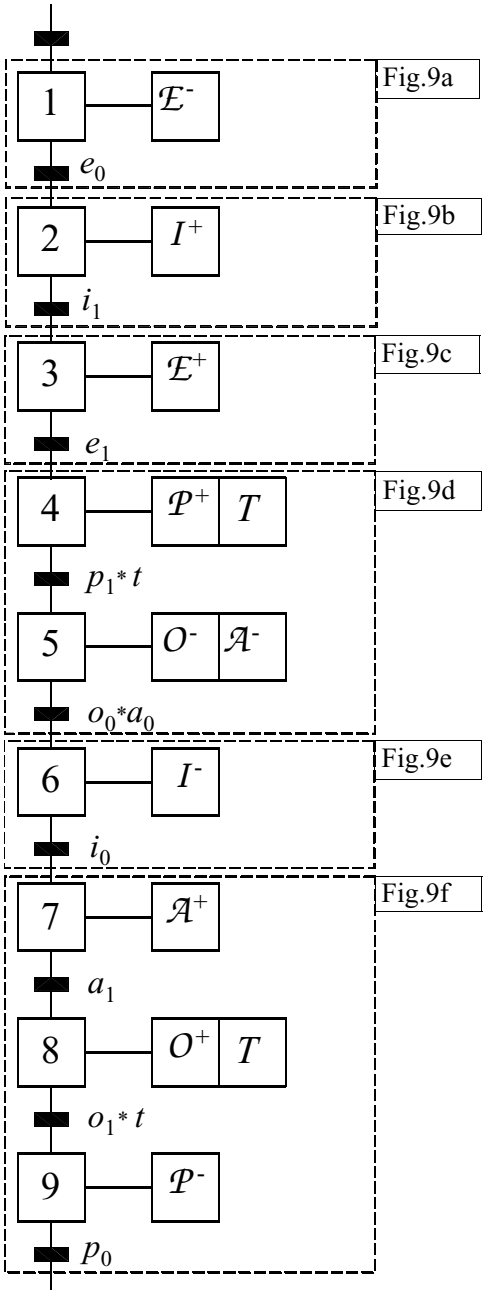


Fig. 8. Grafcet diagram for turning right.

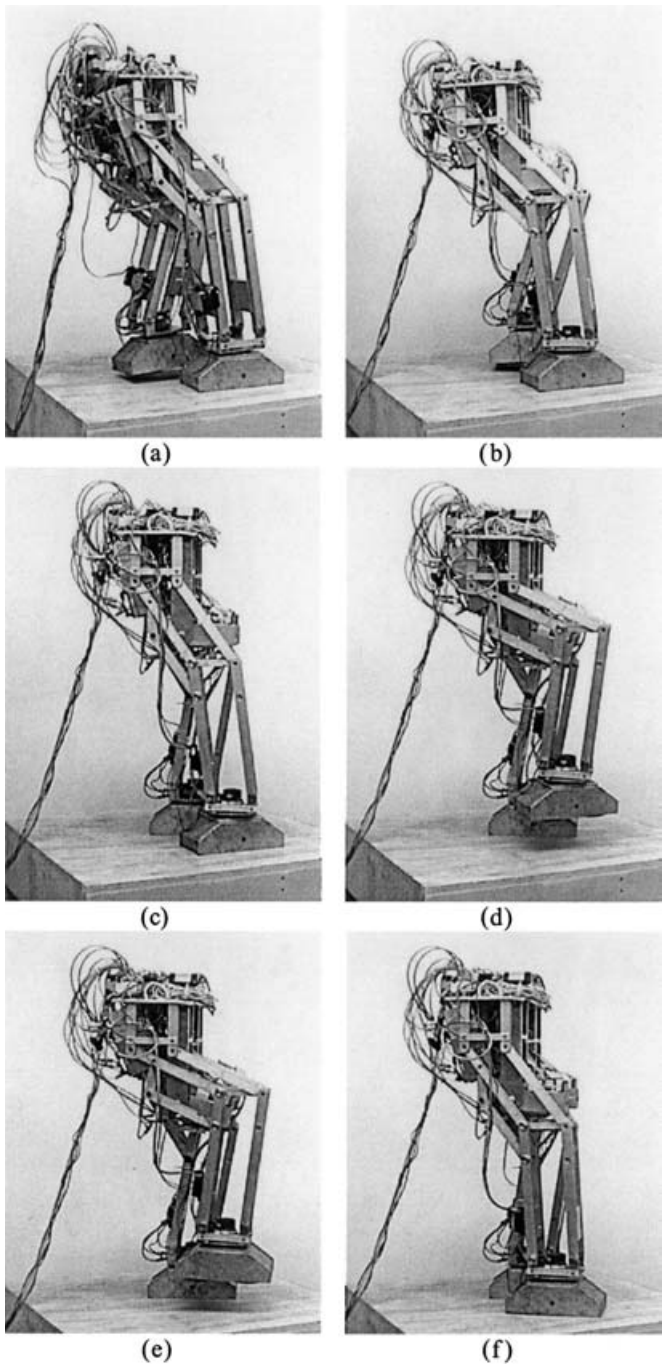


Fig. 9. Experimental test at LARM (Laboratory of Robotics and Mechatronics) with the EP-WAR3 robot prototype turning on the right side, according to the Grafcet diagram of Fig. 8: (a) left foot is lifted; (b) robot body turns right around the right foot; (c) left foot is put onto the floor; (d) right foot is lifted; (e) right foot turns with respect to the robot body; (f) right foot is put onto the floor.

signals $\mathcal{P}^+$ and O^-. The switching of sensors a_0, l_1, a_1, o_1, p_0, e_0, l_0, e_1, p_1, o_0 and the end of time t allow, the transition between the nine phases of the Grafcet of Fig. 10. Therefore, EP-WAR3 is rotated on the left side by 30 deg.

5. MOTION ANALYSIS FOR CLIMBING STAIRS

The basic trajectory for climbing stairs and their elementary actions are analyzed in depth in order to show them as a low-cost design and a suitable programming technique useful to obtain proper performances and maneuverability of the EP-WAR3 biped robot. Two half-steps have been conceived in order to satisfy both situations for which the number of steps is even or odd and the starting configuration of the robot presents a right or left foot forward. The sequences of elementary actions are shown in Figs.12 and 13 in the form of Grafcet diagrams.

Referring to Grafcet of Fig. 12, the sequence of elementary actions has been designed with the aim to have the starting of a subroutine by different configurations of robot: (i) Left foot forward and upstep with its suction-cups operated and right foot back and down-step; (ii) Left foot completely forward with its suction-cups operated and right foot completely back

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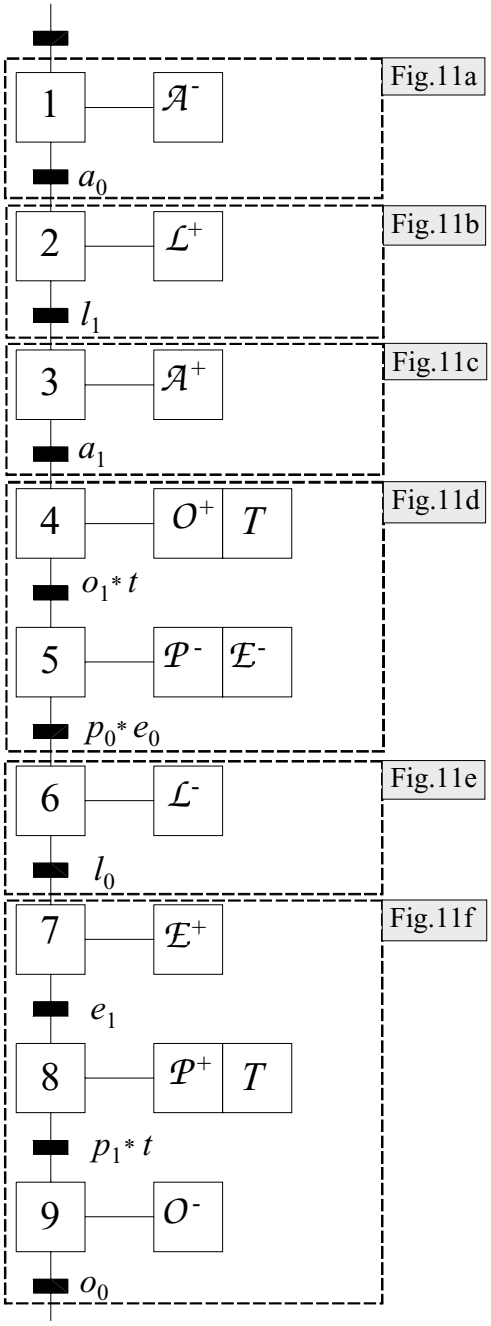


Fig. 10. Grafcet diagram for turning left.

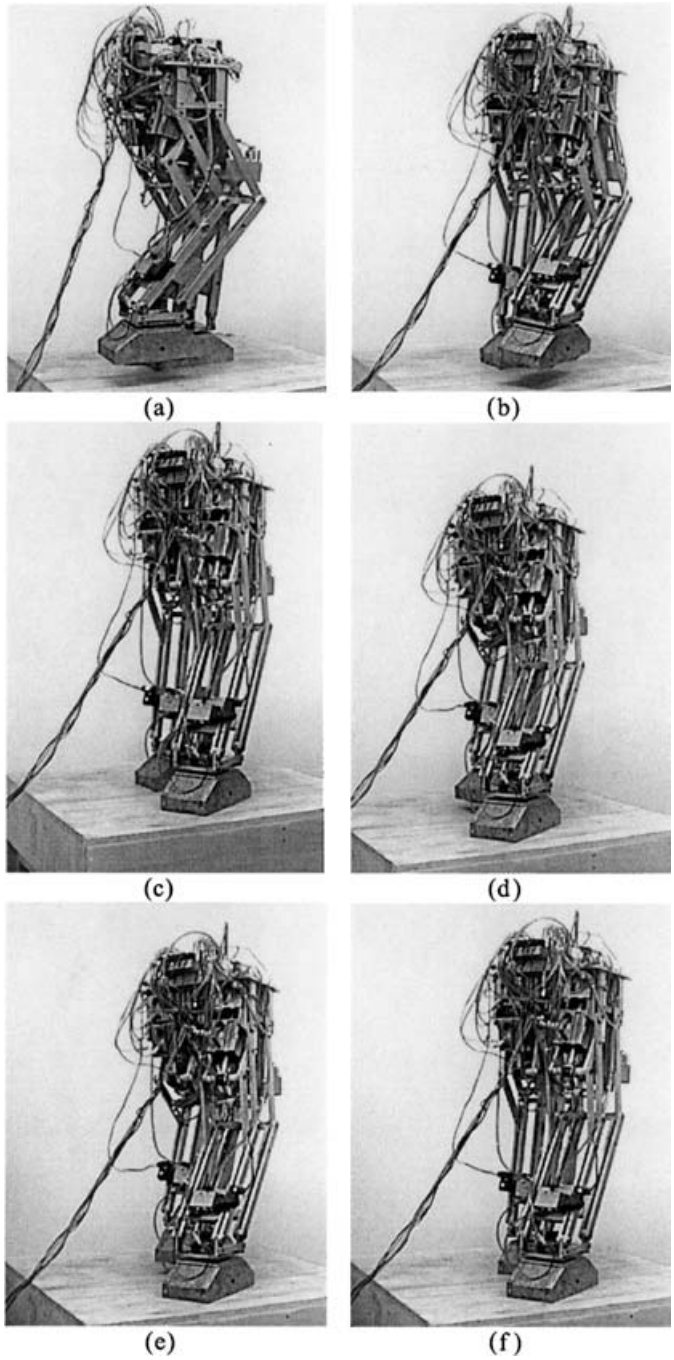


Fig. 11. Experimental test at LARM (Laboratory of Robotics and Mechatronics) with the EP-WAR3 robot prototype turning on the left side, according to the Grafcet diagram of Fig. 10: (a) left foot is lifted; (b) robot body turns right around the right foot; (c) left foot is put onto the floor; (d) right foot is lifted; (e) right foot turns with respect to the robot body; (f) right foot is put onto the floor.

as for performing a long step; (iii) Left foot forward with its suction-cups operated and right foot back as for performing a short step. Thus, some redundant control signals have been obtained for the cases (i), (ii) and (iii), respectively. Similar considerations can be made for the sequence of elementary actions of Fig. 13.

The Grafcet diagram of Fig. 12 describes the performing the right half-step for climbing stairs. In the first phase, signals $\mathcal{A}^-$ and $\mathcal{B}^-$ lift the left foot according to Fig. 14b and in the second phase, signals $\mathcal{G}^+$ and $\mathcal{C}^-$ move the right foot and robot body forward according to the robot configuration of Fig. 14c. Then, the left foot is positioned up-step through the signal $\mathcal{A}^+$, as shown in Fig. 14d. Finally, signal O^+ switches-on the suction cups of the right foot after the time t of timer T and the section-cups of the left foot are switched-off by the signal $\mathcal{P}^-$. The switching of sensors $a_0, b_0, f_1, d_1, g_1, c_0, a_1, o_1, p_0$ and time t allows a transition between the five phases of the Grafcet of Fig. 12. Therefore, the control signal $\mathcal{F}^+$ is redundant because in the experimental test of Fig. 14 both feet of EP-WAR3 are already at same level. Moreover, since the piston of cylinder $\mathcal{H}$ is already outstroke because of the starting configuration of Fig. 14a for a long step, signal $\mathcal{H}^+$ is also redundant.

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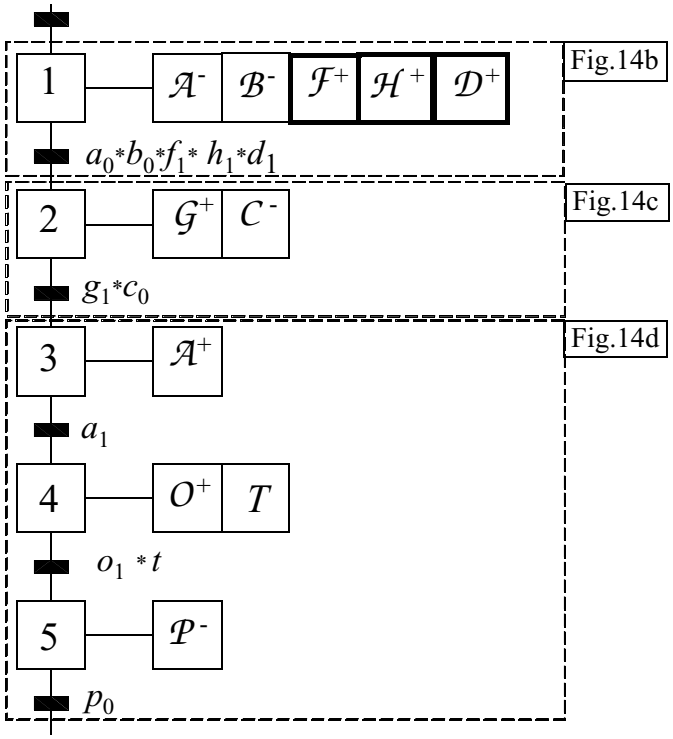


Fig. 12. Grafcet diagram of the right half-step of the EP-WAR3 for climbing stairs (gross lined boxes refer to redundant command signals).

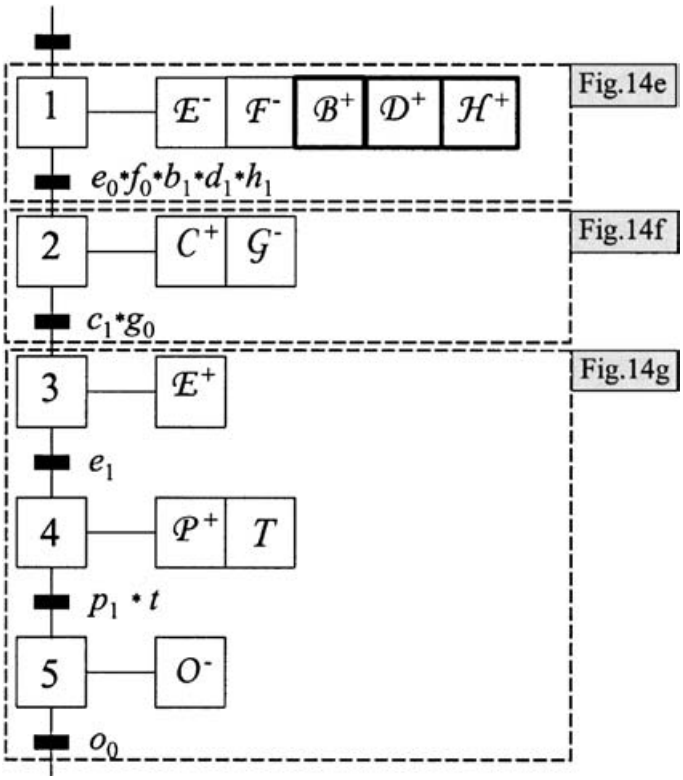


Fig. 13. Grafcet diagram of the left half-step of the EP-WAR3 for climbing stairs (gross lined boxes refer to redundant command signals).

The Grafcet diagram of Fig. 13 is composed by five phases, which show the sequence of elementary actions in order to perform left half-step up-stairs. In the first phase, signals $\mathcal{E}^+$ and $\mathcal{F}^-$ lift the left foot and $\mathcal{B}^+$ pushes down the right foot in order to reach the robot configuration of Fig. 14e. In the second phase, $\mathcal{C}^+$ and $\mathcal{G}^-$ move the left foot and robot body forward to reach the configuration of Fig. 14f. In the last three phases, signal $\mathcal{E}^+$ allows the positioning of the left foot up-step and, finally, the left foot becomes the supporting foot according to the robot configuration of Fig. 14g. The switching of sensors e_0, f_0, b_1, d_1, h_1, c_1, g_0, e_1, p_1, o_0 and the end of time t allow the transition between the five phases of the Grafcet of Fig. 13. Therefore, a sequence of right and left half-steps gives a complete step up-stairs, and EP-WAR3 is ready to perform another right half-step in order to climb stairs with any number of steps.

6. MOTION ANALYSIS FOR DESCENDING STAIRS

The basic trajectory for descending stairs and their elementary actions are analyzed in depth in order to show how it has a low-cost design and a suitable programming technique give a good performances and maneuverability for a EP-WAR3 biped robot. Two half-steps for descending stairs have been conceived in order to satisfy both situations for which the number of steps is even or odd, and the starting configuration of the robot shows the right or left foot forward. Thus, two sequences of the elementary actions have been proposed, as shown in Figs. 15 and 16 in the form of Grafcet diagrams. These Grafcet diagrams refer to the left half-step and right half-step, respectively.

Both Grafcet diagrams have been conceived with the aim to run each corresponding subroutine by different starting configurations of EP-WAR3: (i) Right foot is forward and down-step with its suction-cups operated and left foot is backward up-step; (ii) Right foot is completely forward with its suction-cups operated and left foot is completely backward as for performing a long step; (iii) Right foot is forward with its suction-cups operated and left foot is backward as for performing a short step. Thus, some redundant control signals have been used in the Grafcet of Figs. 15 and 16, in order to descend the stairs by any of the above mentioned starting configurations. These redundant signals are indicated by gross line boxes in both Grafcet diagrams.

In particular, referring to the first phase of the Grafcet of Fig. 15, the control signal $\mathcal{E}^-$ is redundant for the case (i) since the left leg is already lifted partially, while $\mathcal{H}^+$ is redundant for the case (ii) since the left leg is already extended backward. In the third phase, $\mathcal{D}^+$ is redundant for the case (iii) since the robot body is already forwarded partially. In the forth phase, the control signal $\mathcal{M}^-$ is redundant for the cases (ii) and (iii) since it is not used for long and short steps.

Similar considerations can be done for the Grafcet of Fig. 16, where the redundant control signals $\mathcal{A}^-$, $\mathcal{D}^+$, $\mathcal{H}^+$ and $\mathcal{N}^-$ have been used in order to descend stairs by any starting configuration of EP-WAR3 with the left foot forward and right foot backward. This robot configuration is opposite to that given by the Grafcet diagram of Fig. 15.

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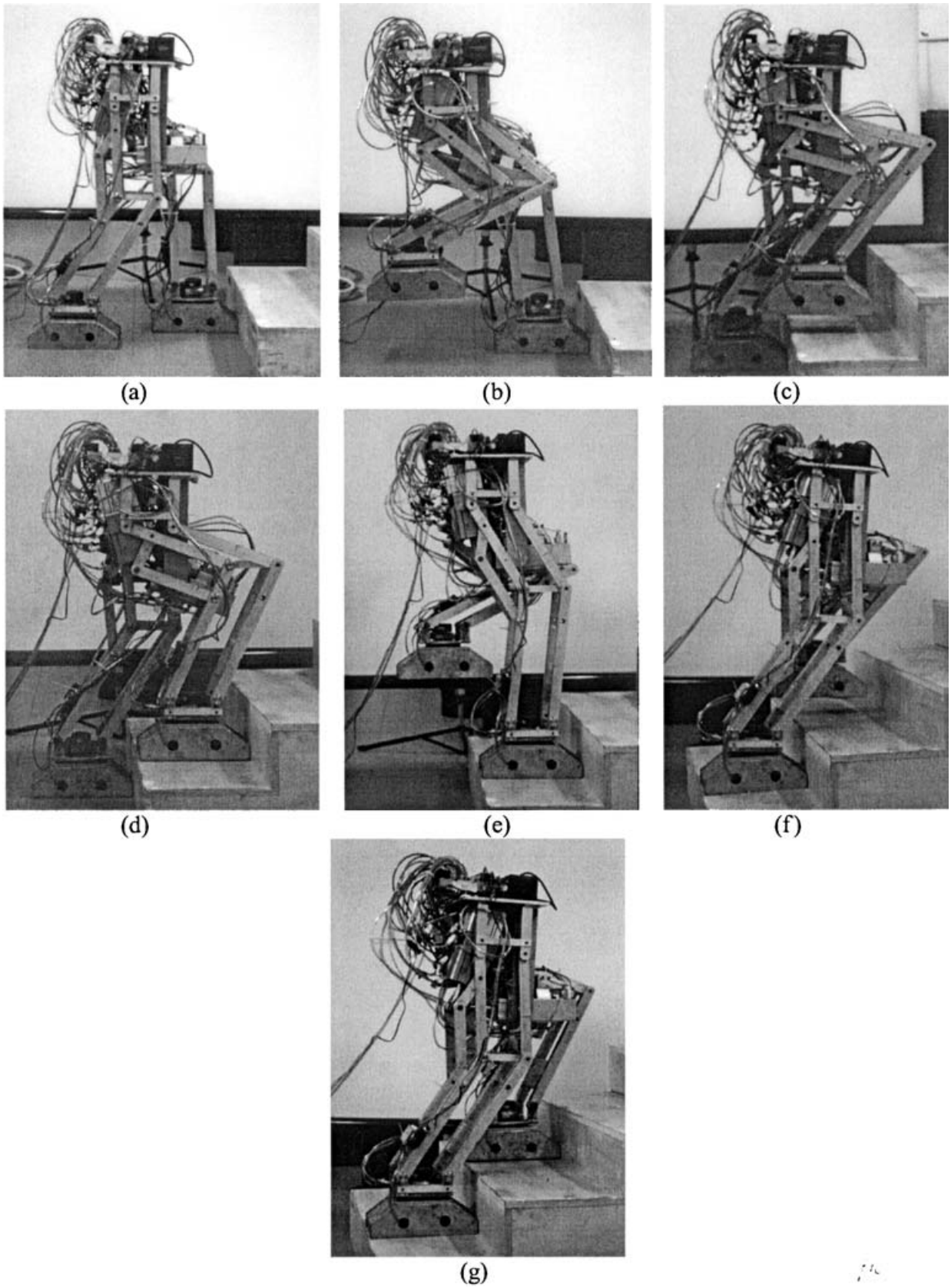


Fig. 14. Experimental test at LARM (Laboratory of Robotics and Mechatronics) with the EP-WAR3 robot prototype climbing stairs in the absolute motion, according to the Grafcet diagram of Fig. 12 and 13: (a) Starting configuration; (b) right foot is lifted; (c) right foot and robot body are moved forward; (d) right foot is put onto the step; (e) left foot is lifted; (f) left foot and robot body are moved forward; (g) left foot is put onto the upper step.

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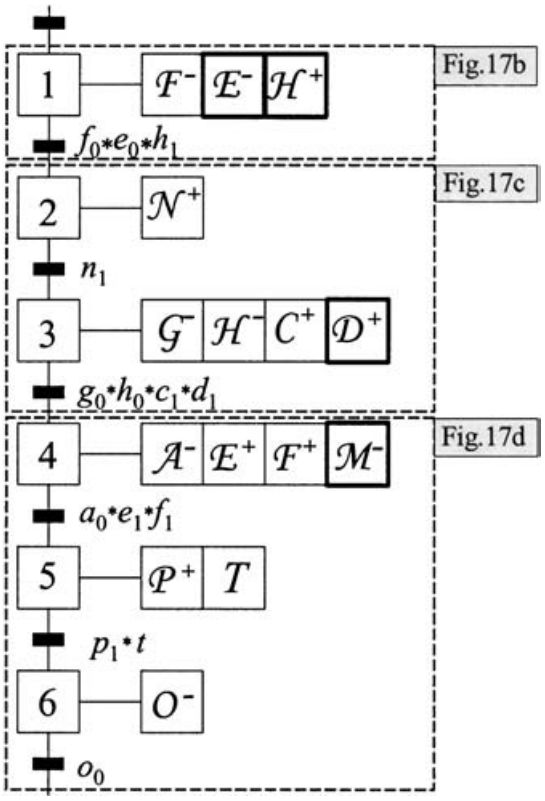


Fig. 15. Grafcet diagram of the left half-step of the EP-WAR3 for descending stairs (gross lined boxes refer to redundant command signals).

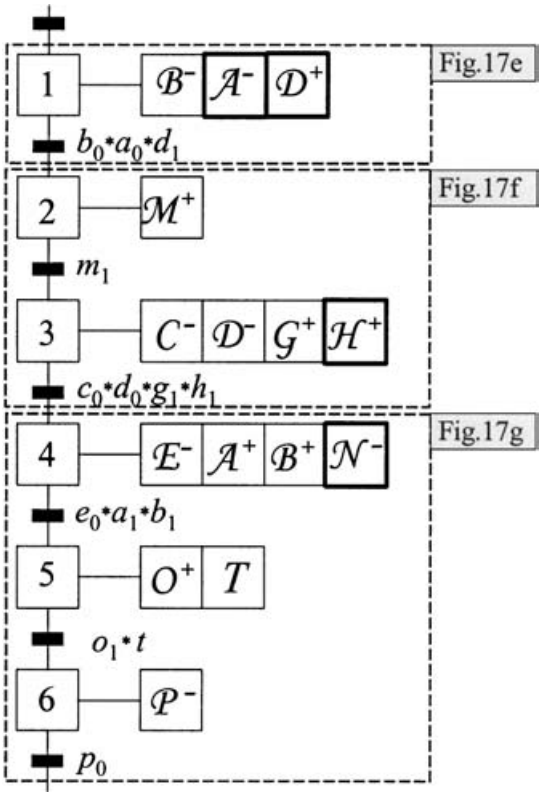


Fig. 16. Grafcet diagram of the right half-step of the EP-WAR3 for descending stairs (gross lined boxes refer to redundant command signals).

In particular, the Grafcet diagram of Fig. 15 is composed by six phases, which show the sequence of the elementary actions in order to perform a left half-step down-step. In the first phase, the control signals $\mathcal{E}^-$ and $\mathcal{F}^-$ lift the left foot completely, as in Fig. 17b, while $\mathcal{H}^+$ prepares the insertion of the slider (2) of the Cardan mechanism of Fig. 1a. Then, $\mathcal{N}^+$ gives the positioning of this slider. In the third phase, $\mathcal{G}^-$ and $\mathcal{H}^-$ move left foot forward, while $\mathcal{C}^+$ and $\mathcal{D}^+$ move the robot body forward. Consequently, the robot configuration of Fig. 17c is reached. In the fourth phase, signal $\mathcal{A}^-$ bends the right leg, while $\mathcal{E}^+$ and $\mathcal{F}^+$ let the positioning of the left foot down-step, as shown by Fig. 17d. Thus, the left foot becomes the supporting foot through the phases five and six, where the suction-cups $\mathcal{P}$ are operated after the time t of the timer T and the suction-cups O of the right foot are switched-off. The control signal $\mathcal{M}^-$ moves back the slider (2) and the Cardan mechanism is back at the starting position. The on/off feedback sensors e_0, f_0, h_1, n_1, g_0, h_0, c_1, d_1, a_0, e_1, f_1, p_1 and o_0 together with the signal t of the timer T, allows the transition through the six phases of the Grafcet diagram of Fig. 15.

Similarly, the Grafcet diagram of Fig. 16 gives the elementary actions for the right half-step during the descending of stairs. The control signals $\mathcal{A}^-$ and $\mathcal{B}^-$ lift the right foot completely, while $\mathcal{D}^+$ prepares the insertion of the slider, which is positioned by $\mathcal{M}^+$. EP-WAR3 assumes the configuration of Fig. 17e. In the third phase, $\mathcal{C}^-$ and $\mathcal{D}^-$ move the right foot forward, while $\mathcal{G}^+$ and $\mathcal{H}^+$ move the robot body forward by reaching the configuration of Fig. 17f. In the fourth phase, $\mathcal{E}^-$ bends the left leg, while $\mathcal{A}^+$ and $\mathcal{B}^+$ give the down-step position of the right foot, as shown in Fig. 17g. Thus, the right foot becomes the supporting foot through the phases five and six, where the suction-cups O are operated according to the timer T and the suction-cups $\mathcal{P}$ of the left foot are switched-off. The control signal $\mathcal{N}^-$ moves the slider back to the starting position. The on/off feedback sensors a_0, b_0, d_1, m_1, c_0, d_0, g_1, h_1, e_0, a_1, b_1, o_1 and p_0 together with the signal t of the timer T, permit the transition through the six phases of the Grafcet of Fig. 16. Therefore, the EP-WAR3 robot prototype is ready to perform another left half-step, in order to descend the stairs with any number of steps.

7. CONCLUSIONS

A specific research has been carried out at LARM (Laboratory of Robotics and Mechatronics) in Cassino, in order to design, build and test a low-cost biped robot prototype, named EP-WAR3 (Electro-Pneumatic-WAlking-Robot), which is able to move autonomously in structured environments. EP-WAR3 is provided with a binary pneumatic actuation and controlled through a PLC as an event-based system in an on/off environment. The validation of the walking capabilities of EP-WAR3 has been carried out through several experimental tests at LARM, which have shown suitable performances for walking straight, turning right and left, climbing and descending stairs.

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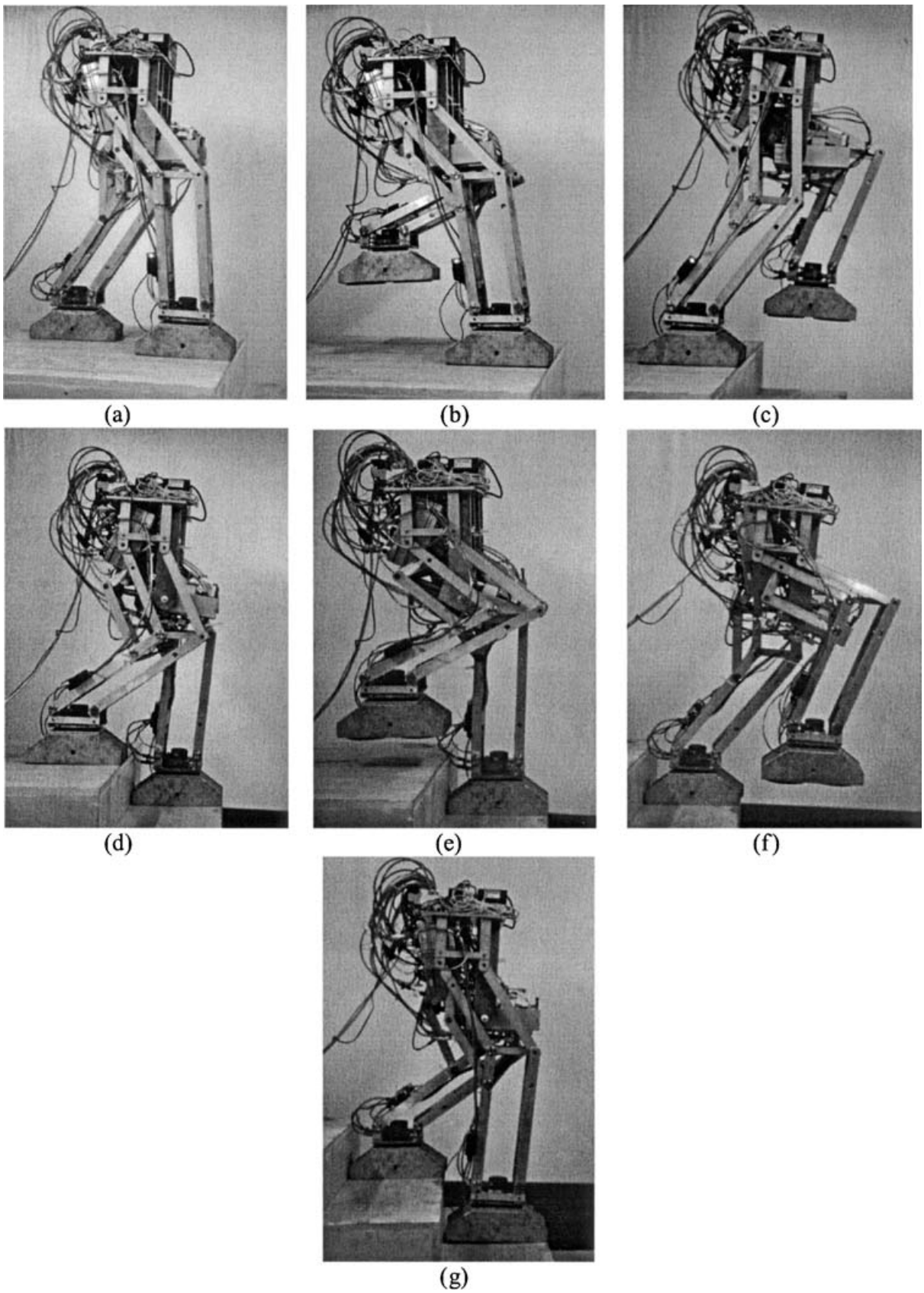


Fig. 17. Experimental test at LARM (Laboratory of Robotics and Mechatronics) with the EP-WAR3 robot prototype descending stairs in the absolute motion, according to the Grafcet diagrams of Figs. 15 and 16: (a) Starting configuration; (b) left foot is lifted; (c) left foot and the robot body are moved forward; (d) left foot is put onto the down-step; (e) right foot is lifted; (f) right foot and the robot body are moved forward; (g) right foot is put onto the down-step.

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