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Climbing Robots' Mobility for Inspection and Maintenance of 3D Complex Environments

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Abstract. For complex climbing robots, which work in difficult 3D outdoor environments, the gravity force has an important influence with respect the robots changes during its motion. This type of climbing robots is self-supported in the complex 3D structures (bridges, skeleton of the buildings, etc.) which require periodic, manually performed inspections and maintenance. The use of non-conventional climbing robots for this type of operation is highly appropriate. Their locomotion system commonly comprises arms/legs that permit the robot's 3D mobility (gait). These mechanisms also enable the robot to support itself and guarantee its stability. This paper presents the main features of non-conventional climbing robots' mobility on complex 3D environments: power supply, number of DOFs, lightweight structure, gait, speed, secure grasp, etc. It also covers the general theory underlying the design of climbing robots, their kinematics, with its specific, unconventional mobility. The paper not only describes the climbing robot mobility theory but also provides several examples taken from the ROMA and MATS robots families. The developed robots have high degree of autonomy with totally on-board control system. These autonomous robots demonstrate in the course of real experimentation that the criteria for design, control strategy and path planning are accurate. Finally, the paper examines trends in climbing robot technology.

Keywords: climbing robots, kinematics, mechatronical design, path planning, control strategy, inspection and maintenance applications

1. Introduction

Inspection, maintenance and cleaning operations of civil infrastructures, such as: bridges, buildings skeletons', complex roofs, offshore platforms, etc., are very important tasks. They are estimatelly over 42.000 steel bridges in the EU, most of them with replacement values of up to 350 MEuros, and there are also estimatelly 210.000 and 270.000 steel bridges, respectively in the USA and in Japan. Similar operations can be performed in the high-rise steel-based building's skeleton during its erection where all the beams' joints must be tested. Every year, there are thousands of workers' accidents in construction sites, being these accidents about 25% of the total ones. Figure 1 shows two main areas of inspection applications and their human operator work.

The periodical inspection, maintenance and cleaning of these infrastructures involve a high number of dangerous manual operations and represent a danger even for skilled workers. The main testing parameters are: the quality of painting or protection of steel-based beams and columns (to avoid corrosion), the quality of part fixers, like fasteners, rivets, screws, etc. and welded joints (to avoid collapsing), the clearness of the pipes, surfaces, supporting beams, etc. (to avoid pollution), etc. This is why the development of autonomous non-conventional climbing robots is very important from different points of view: safety of the infrastructure, safety of the human operators, quality of the inspections and increment of the periodicity of inspection.

Unlike wheeled and legged robots, climbing robots need to be self-supported in the environment without

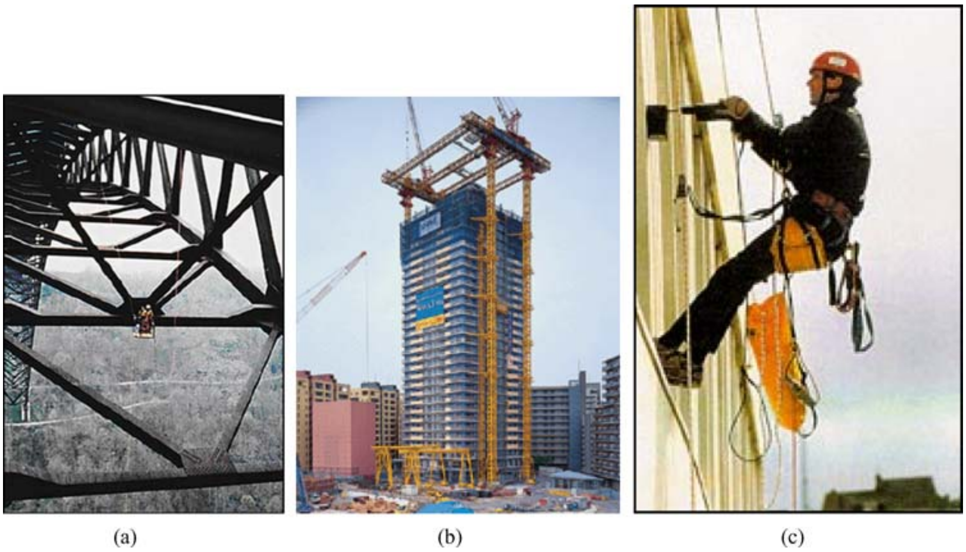

(a) (b) (c)

Figure 1. Different climbing environments: (a) steel-based bridge, (b) building steel-based skeleton, and (c) its manual inspection.

stable connection to the "grounds". The climbing robot can be in horizontal or vertical position and sometimes it can be inverted and can work in suspension. There are two different types of climbing robots: (a) robots that move on flat or quasi-flat surfaces and (b) robots that change from one plane to another performing 3D motion.

The first type of climbing robots is that of those that move in flat or quasi-flat surfaces without change of plane. For them, the gravity force actuates not vertically with respect the robot's base (located in the ground), but it always actuates along the robot's body. The mobility of these robots is well known and it is based on parallel or circular movements similar to the grasping devices (electromagnets or pneumatic suction pumps). Their main surfaces of movement are: glass façades or concrete walls (for cleaning) (Schraft et al., 2002), steel ship body (for welding and inspection) (de Santos et al., 2000), steel oil storage tanks (for inspection) (Gradetsky, 2003), aluminum aircraft fuselage or wing (for inspection) (Alexander et al., 2003), etc.

Nevertheless, most infrastructures have complex 3D structures (bridges, buildings skeletons, off-shore platforms, etc.). To use the climbing robots in this environment it is necessary to continuously move changing from one plane to another, from one beam to another or from one face of the beam to another. The main applications are: corrosion control, using color cameras that transmit images to the "ground" computer to be processed, welding joints inspection, using X-ray sensors, rivet or screws control, using vision and/or lasers, etc. The mobility of this type of climbing robots is not yet defined and there are only a few robots of this type. They are, at the same time, a big social need and there is a big market for them.

Only few robots of the second type were developed in the past. One of the first ones were the Robug family robots (Luk et al., 1993) developed by Portech. They were heavy and its mobility in 3D environment was limited. The latest improved version Robug IV (Cooke et al., 1999) maintained the umbilical connection with the "ground" based control system. The Lemur II (Kennedy et al., 2001) quadruped rock-climbing robot, despite it good mobility in the plane, does not demonstrate its movement from one plane to another.

This paper presents the theory of mobility for the non-conventional (second type) climbing robots moving among 3D complex environments. The main features of the robot design have been analyzed. Most of these features are taken into account during the development of several climbing robots at University Carlos III of Madrid: the ROMA family climbing robots for in-service inspection of infrastructures (Balaguer et al., 2002) and the MATS robot for elderly and disabled people assistance (Gimenez et al., 2003).

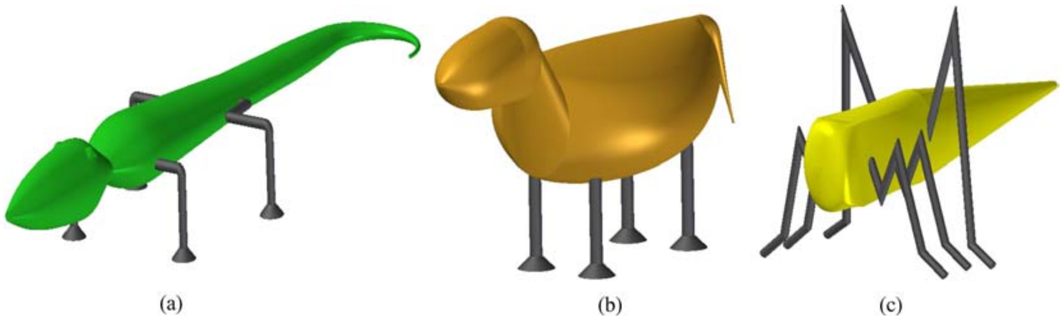


Figure 2. Different type of nature locomotion: (a) reptiles, (b) mammals and (c) insects.

2. Biologycal Inspiration of Climbing Robot Mobility

To establish the theory of climbing robots mobility it is necessary to observe or study the nature. The great adaptation of animals to climbing has been a source of inspiration and study for the most of the climbing robots designers. Insects and vertebrated animals have the skill to travel along tree trunks and branches. Within the animal kingdom there are three big families that have been thoroughly studied: reptiles, mammals and insects. They have a high degree of evolution in their mobility systems. All of them have been studied in order to know more about its way of locomotion. The main features and structural adaptations for the locomotion of these three groups are as follows (see Fig. 2):

- **Reptiles**
  - Legs in the lateral part of the body
  - Good stability
  - Consume energy even when idle
- **Mammals**
  - Legs in the direction of movement
  - Require higher effort for stability control
  - Medium energy consumption during movement
- **Insects**
  - Legs bigger than the body
  - High stability
  - Low energy consumption

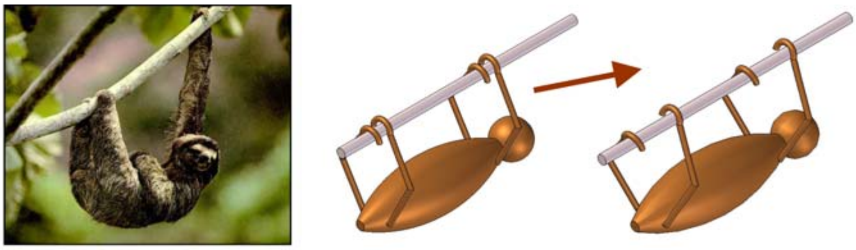
Most of the analyzed vertebrated animals and insects are not specialist in climbing. But others species have singular characteristics in order to move in very complex environments. The best animals adapted to climb have its centre of gravity very low, high stability and relatively high ratio force/body weight. This allows the gripping torques to be very low. Their ways of locomotion are very different. Hildebrand (1995) classified them in (see Fig. 3):

- **Sliding**, walking, and hopping: sloths, squirrels, capuchins, proboscides (Fig. 3(a)),
- **Swinging**, hanging, jumping (with one arm support): orangutans, languorous, chimpanzees, gorillas (Fig. 3(b)),
- **Extension**, shrinking: worm, snake (Fig. 3(c)),
- **Jumping** (without support): grasshopper, frog (Fig. 3(d)).

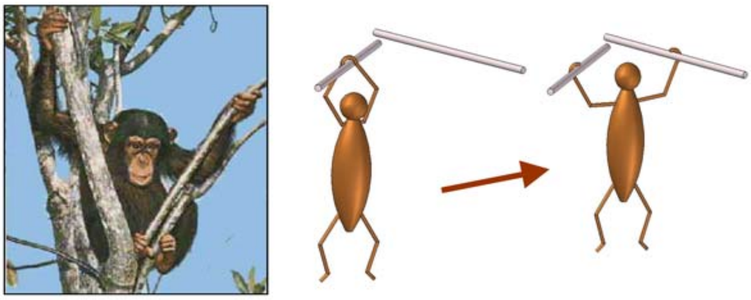
Table 1 shows the comparison among different locomotion systems of the described animals. Features like speed, weight and power consumption are relatives and are related to the animals body volume.

Table 1. Comparison of the different locomotion systems' features.

	Locomotion method	Movement direction	Speed	Weight	Power consumption	Locomotion legs/arms
Sloth	Discrete sliding	Straight line	Low	Medium	Low	2/2
Chimpanzee	Swinging	Omni-directional	High	High	Medium	2/2
Worm	Continuous sliding	Straight line	Low	Low	Very low	Many
Grasshopper	Jumping	Straight line	Very high	Low	Low	6

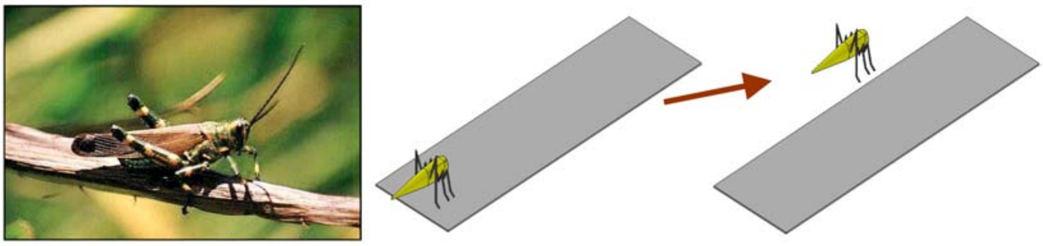


a) Sloth moving along a tree branch without releasing all extremities at the same time.



b) Chimpanzee jumping from one branch to another by releasing one or both arms at the same time.

c) Worm moving by extension-compression.



d) Grasshopper jumping from one position to another.

Figure 3. Different climbing strategies of nature: (a) sloth, (b) chimpanzee, (c) worm and (d) grasshopper.

Referring to the movement direction feature, the mentioned table shows that chimpanzees are the best choice for omni-directional movements. Its swinging or jumping (commonly with one arm support) allows quick change of motion direction keeping a high velocity. Chimpanzees are also the best choice in the number of legs/arms. Commonly using only two extremities (arms) and sometimes, if it is necessary, both legs and arms. On the other hand, worms have the lowest power consumption (also, the lowest speed). The future discussions will be based on the climbing robot structure formed by two legs/arms. Perhaps, creating a new artificial device (climbing robot) which merges the chimpanzees and worms best features, will allow to optimize the robot design (number of legs/arms) and its mobility (directionality, speed, consumption).

An important aspect when a robot must climb is to consider the way of gripping animals have. The basic physic principles that reflect the gripping force is the friction forces produced between the animal appendixes and the surface. It is important to consider that the grasping contact is produced between an elastic surface (climbed surface) and a viscoelastic extremity of the animal (fingers, palm, etc.), so the friction force is bigger. Another possibility is interlocking: a cushion like the footpad that contacts both microscopic and macroscopic projections on a climbed surface using interlocking to prevent from slipping. At last, it is possible to make a dry or capillary adhesion, using a suitable adhesive produced by the animal. The main ways of grasping of most of the specialized climbing animals are summarized as follows:

- **Grasping**. The animal encircles a twig or a trunk tree with its fingers and palms creating high friction forces. These forces increase the frictional resistance to avoid slippage. This kind of grasping is used by chameleons, koalas, spider and woolly monkeys.
- **Balancing**, bracing. This kind of climbers can move quickly between branches. They must be effective balancers, controlling the position of their centre of gravity, at each instant. They have long and strong extremities. This kind of grasping can be seen in: squirrels, titis, orangutans.
- **Clinging**, hooking. These kinds of animals have much curved claws to cling to the substrate. The tips of the claws interlock with small cracks and gaps in the grasping surface. Primates, marsupials, sloth are good examples of this type of grasping.

  Adhering. Some animals have gland in their appendages which produce a sticky secretion to adhere to a surface. This system is used by frogs and salamanders. Geckos use a dry adhesion with a high degree of force even when the animal is dead.
- **Suction**. Some bats have suction cups on knuckles and ankles that work like a man made suction cup. An elastic tissue, without muscular tension, maintains suction within the disk once it is placed.

As conclusion of this last analysis, the grasping mechanisms present a wide variety of possibilities. Grasping is, of course, the most common grasping method. It uses hand (finger and/or palm) to perform friction anti-sliding grasp. This method can easily be reproduced by conventional parallel or circular movement grippers. A negative aspect of this type of grasping is the force that is needed to avoid sliding over the tree branch or tree trunk. On the opposite side the suction method can be found. It has a very strong grasping (adherent) force. Their artificial imitation can be easily performed by using suction pads. Some of these grasping mechanisms, like electromagnets (used by conventional climbing robots moving over metallic surface), do not exist in nature. Nevertheless, they are limited to move in special type of climbing surfaces.

3. Climbing Robot Design Criteria

For the successful development of the autonomous climbing robots of the second type it is necessary to develop the design process concept. The design process of conventional manipulators or mobile robots is well known. There are several packages (Matlab, RobCad, etc.) that help the designer to select the robot's kinematics, actuators, etc. Nevertheless, the design of non-conventional climbing robots is a totally homemade process. As a first step, the design goals need to be defined. The main bottleneck of climbing robots is the overall weight, due to the fact that they are self-supported. Several factors influence in the weight: number of DOF, kinematics, payload, etc. It is interesting to mention that the design process is performed in an iterative way (Gimenez, 2000).

An example of this process is as follows. Initially, the overall weight (including actuators) of the robot is considered. Then, dynamical calculation shows that the reduction of the actuators weight (motors and gearboxes) is possible. With this reduction the overall weight of the robot is also reduced. If the robot's weight is reduced again it is possible to select lighter actuators, etc. This process has a minimum value that is considers an optimal solution for robot's design. Note that the described iterative process works also in the opposite direction.

As it was shown before, the overall weight of the robot is one of the most important criteria during the design of climbing robots. Other important criteria must be taken into account, such as: the mobility, number of DOF, the motion speed, the robot's kinematics, etc.

The most important criteria are described in the next subsections.

3.1. Mobility Criterion

The robot's mobility is closely related with the number of DOF. By increasing the number of DOF, it is possible to increase the robot mobility. But at the same time the overall weight of the robot is also exponentially increased. Figure 4 shows this relation for conventional design process using conventional actuators. This data was obtained during iterative process of increasing the number of DOF by introducing a new motor in the ROMA I robot's structure, which obviously increased the overall weight of the robot and the weight of the previous motors that supported more torque now (Gimenez, 2000).

On the other hand, for inspection of 3D structures, like bridges and building skeletons, a high level of mobility is needed, i.e. it is necessary to visit all the faces of the metallic structure (beam and columns). Let's consider an example of the climbing robot's motion from face A1 to face A2 of the beam. Figure 5(a) shows that it is possible to perform this transition with a 6 DOF kinematics. But the robot can also move from A1 to A2 by only using 4 DOF via intermediate faces: from A1 to C1, from C1 to B1, and finally from B1 to A2 (Fig. 5(b)). Having in mind this fact, it could be possible to optimise the robot's path planning in order to visit all faces of the 3D structure and to decrease the overall inspection time. This path planning algorithm can be based on the TSP (o similar) algorithm that guarantes the visit of all the faces of the inspected structure with minimum numbers of faces visited (Padron et al., 2000).

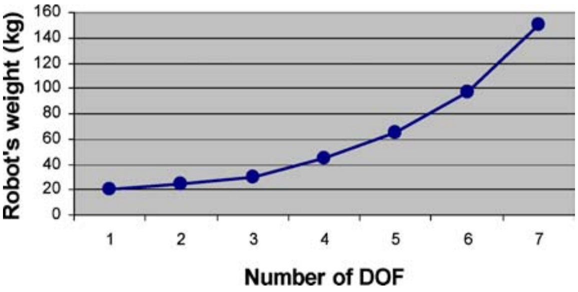
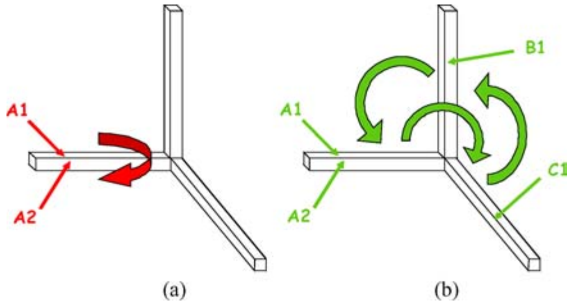


Figure 4. Relationship between the robot's weight and the number of DOF (for conventional design).



(a) (b)

Figure 5. Mobility criterion depends on the number of DOF: (a) 6 DOF, and (b) 4 DOF.

As conclusion of this example, the mobility criterion can be formulated: *It is possible to reduce, without loss of overall mobility, the number of DOF (weight) of the climbing robot by planning its paths by optimizing the travel features (time, space, energy).*

3.2. Symmetrical Criterion

The common manipulators have more powerful (heavier) actuators in the base and less powerful (lighter) actuators in the tip. It is easy to understand this design structure due to the fact that the first DOF moves the entire robot and the last one moves only the gripper's tool. The base of conventional manipulators is fixed and normally attached to the floor or to other static parts. In the case of non-conventional climbing robots moving in complex 3D environments the concept of base or tip is not clear. During the climbing process sometimes the base will be the base and sometimes it will be the tip. It depends on the mobility strategy. Figure 6 shows that depending on the mobility strategy, during the transition from the horizontal to the vertical plane, the arm A is in the upper or lower position.

In the same way that chimpanzees have the same power in both arms, the climbing robot must have the possibility to be attached to the environment by one arm (side) or by another. This fact makes that the torque needed by the actuators on the base (tip) must be exactly the same that in the tip (base). Figure 6 also shows that depending on the mobility strategy the arm that moves all the robot's body is for example A or its opposite. It means that the robot must be symmetrical.

The symmetrical criterion can be formulated as: *The climbing robot formed by the body and two or several extremities (arms/legs) must be symmetrical (in kinematics and dynamics senses) with respect to the centre of the body.*

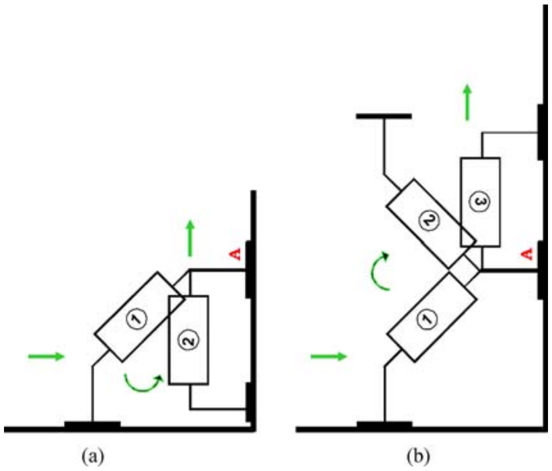
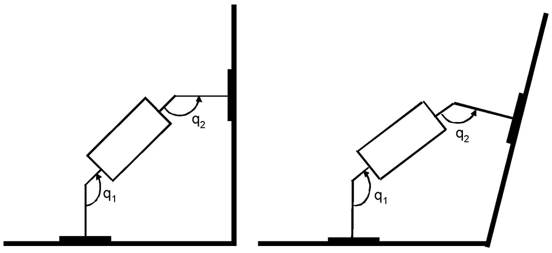


Figure 6. Symmetrical criterion depends on the mobility strategy: (a) worm inspired, and (b) acrobat inspired.

3.3. Symmetrical Movement Criterion

Figure 6 shows two possible different climbing strategies in the transition from the horizontal to the vertical plane. It is interesting to note that both strategies have big similitudes; the values of the angles legs/arms with respect to the robot's body are numerically the same but with different sign. Figure 7 shows an example of two transitions an two different environments: perpendicular (a) and non-perpendicular (b) surfaces. The angles q_1 and q_2 are the same in both paths.

This important analysis leads to the conclusion that instead of using one actuator for each joint it is possible to use one actuator to move both q_1 and q_2 joints. The movement from one plane to another will be produce by using symmetrical angles. It is obvious that by using only one actuator instead of two, the overall robot's weight is substantially decreasing. This is why the most distant motor on the tip of the robot moves to the middle position, reducing the necessary actuator torque, leading to the reduction of the weight of the actuator, that finally reduces the overall weight of the robot.



(a) (b)

Figure 7. Symmetrical movement criterion for different surfaces transitions: (a) perpendicular and (b) non-perpendicular surfaces.

The symmetrical movement criterion, which is really part of the symmetrical criterion, is formulated as follows: *Some joints of the climbing robot formed by the body and two or several extremities (arms/legs) can be moved symmetrically by only one actuator.*

3.4. Maximum Gait Criterion

One of the important features of climbing robots is the maximum gait generation during the movement. It is important from the speed (productivity) point of view and also from the energetic point of view. The robot's on-board power is simply very limited and the fact of performing longer gait helps to economize the energy.

Figure 8 illustrates two different gaits for climbing robots. In the first case (Fig. 8(a)) the robot moves as a caterpillar (worm) shrinking and extending it body. The robot can overcome a distance d with prismatic joints. If this prismatic joint is replaced by two rotational joints, situated at the extremities of the robot's body, the overcome distance, D, would be much longer (Fig. 8(b)). In this case the movement of the robot is similar to a hen or chicken extending and pulling the arms generating robot's maximum gait. Distance D depends on the initial distance of the legs/arms. To maximize D the legs/arms need to be as close as possible. The negative effect of this structure is that the stability decreases, but this problem will be solved designing "low" robots.

The maximum gait criterion can be formulated as follows: *To maximize the travelled distance in one robot's gait it is necessary to use rotational joints and initially placed the legs/arms as close as possible.*

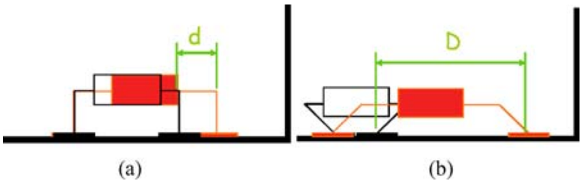


Figure 8. Maximum gait criterion: (a) conventional gait, and (b) maximum gait.

4. Climbing Robot's Mobility Examples

Appling the criteria described in the previous section several climbing robots were developed at the University Carlos III of Madrid during the last years. Each one of them has been applied to inspection and maintenance operations in different environment conditions. ROMA I robot (Balaguer et al., 2002) was developed to inspect mainly the steel-beams based infrastructures like bridges, skeletons of the buildings, etc. Its grasping mechanism is able to securely grasp beams and columns. The ROMA II robot (Gimenez et al., 2001) was designed to travel along concrete, wood or plastic surfaces by using a suction cups mechanism. Its weight was substantially reduced by using several of the above described design criteria. Finally, the recently developed robot MATS (Balaguer et al., 2003a) allows to move along the domestic interior environment by using specially located docking stations. Being the robots' mobility different in some aspects, it was demonstrated that climbing in a complex 3D environment is possible with a high level of security.

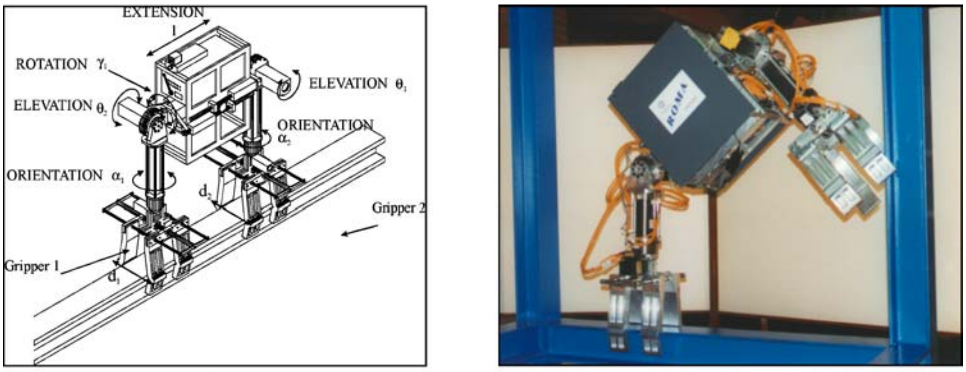
4.1. ROMA I Robot

The ROMA I robot structure consists of two essential parts: (a) the body of the robot, and (b) the robot arms. The body of the robot includes all the vital parts of the robot: the on-board computer, the servo multi-axis controller board, the radio-based Ethernet communication with the "ground" operation center, and other auxiliary electronics. The body is also "responsible" for the power supply.

The kinematics of the ROMA I robot has been inspired in the locomotion of caterpillars or worms. This insect moves along the branch extending and shrinking of its body. The robot's arms represent its locomotion system. The ROMA I robot has two arms in order to attach and detach the robot from the structure. The robot is designed to climb along metallic-based structures formed by beams and columns. ROMA I robot has two grippers to accomplish this task, working with the *grasping* method. The grippers encircle the beam creating a high degree of friction force, to avoid the slippage.

The ROMA I (Fig. 9) (Balaguer et al., 2000) has 8 DOF, 2 for opening and closing each gripper (a prismatic joint for each gripper for the closing and opening movements), and 6 for the motion of the robot. The robot's 6 DOF are: (a) two elevation and two orientation joints for each of the grippers, (b) one rotation joint for gripper 2, and (c) one prismatic joint for the body "*extension*".

Using ROMA I kinematics it is possible to travel in different planes and to perform different transitions. Figure 10 presents some examples of its movements. During phases (a) to (c) the robot moves horizontally by consecutively extending and shrinking. During phase (d) the robot transits from the horizontal plane to the vertical one by coordinating, in first place, elevation and extending, and then by vertical adaptation and shrinking. The grasping forces during this operation must be carefully controlled. In phases (e) and (f) the robot moves in the vertical plane by also extending and shrinking. These movements can be done in other planes due to the high number of DOF the ROMA I robot has.



(a) (b)

Figure 9. ROMA I robot: (a) kinematics structure and (b) picture in the beam-based structure.

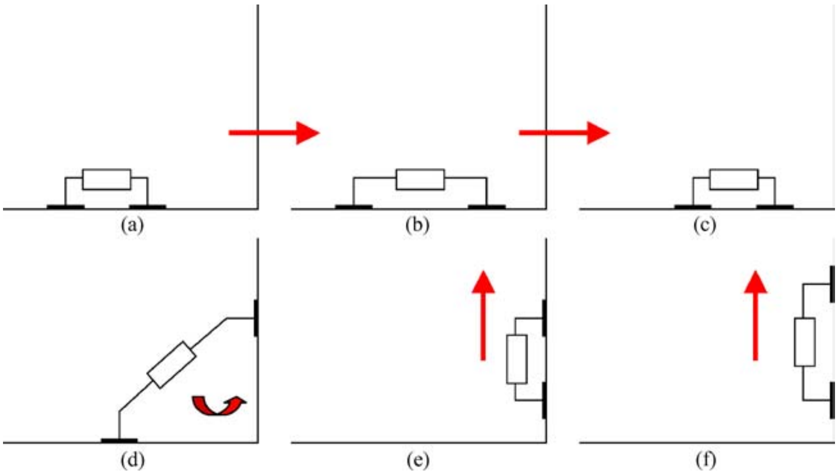


Figure 10. Motion sequence of the ROMA I robot during the transition from the horizontal to the vertical plane.

4.2. *ROMA II Robot*

The ROMA II robot introduces simpler kinematics structure, lighter actuators and lighter materials (Nardelli et al., 2003). The robot uses the symmetrical criterion by reducing the number of actuators and uses only one actuator, located in the middle of the body, to move two joints (q_3) at a time (Fig. 11(a)). The robot has only 4 DOF but big mobility due to the mobility criterion. The overall robot weigh is about 25 kg, its velocity is about 1.5 m/min, and its payload is 5 kg. The vacuum system is able to produce a grasping force of 100 kg. There are two arm platforms with 10 vacuum cups, which are connected in pairs. For this reason if one of the vacuum pair of cups does not work, there is only one pair that cannot stick to the surface. The required compressed air pressure is about 6 bar for an adequate system performance.

On the other hand, not all joints are required to have the same high level of accuracy of the movements. Those joints requiring maximum accuracy should be driven by electrical actuators, and those joints which movements are not be very precise (but need more force) can make be driven by lighter actuators. The ROMA II robot has mixed actuators. There are electric actuators to perform movements with a high degree of

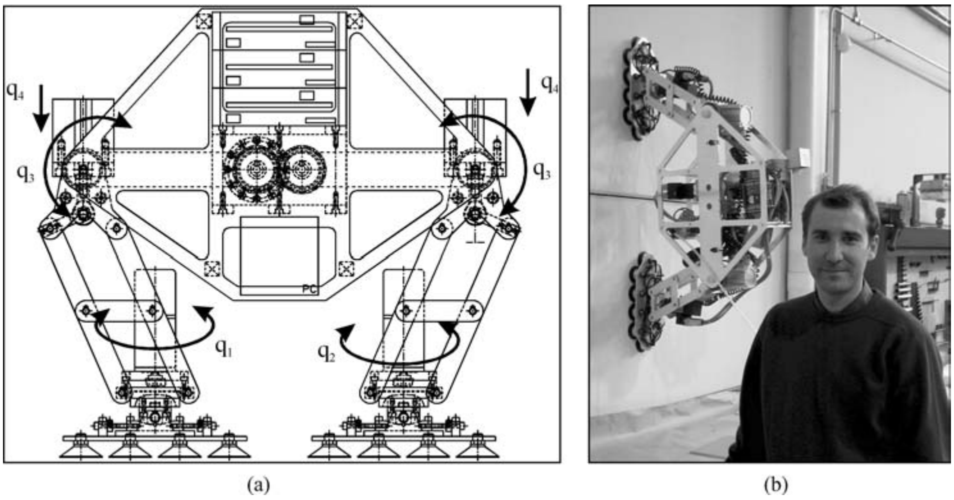


Figure 11. ROMA II robot: (a) kinematics structure and (b) picture in a specific wall.

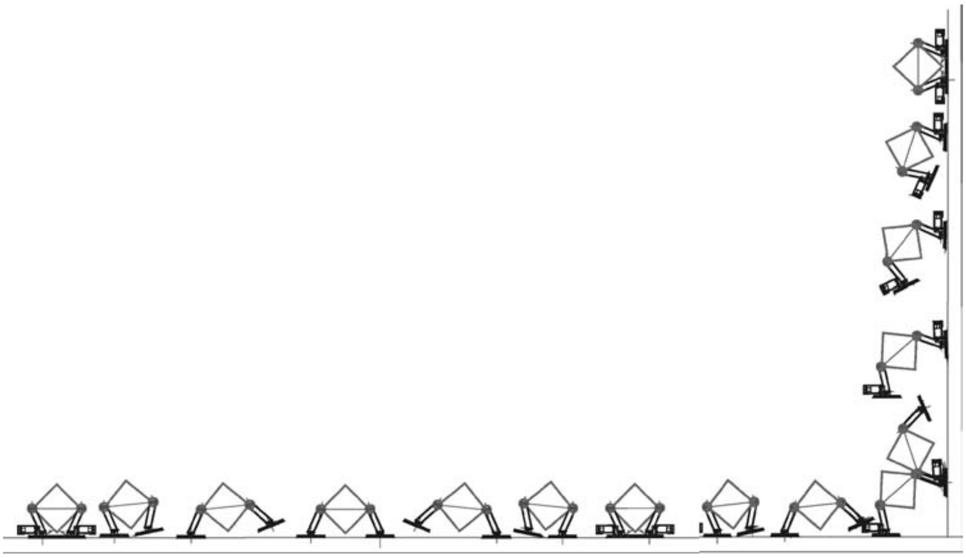


Figure 12. Motion sequence of the ROMA II robot during a horizontal plane travel and during the horizontal to vertical plane transition.

precision and with a medium torque/weight ratio, pneumatic actuators for movements where it is required a maximum torque/weight ratio, and a low degree of accuracy. To grip the robot to the surface, vacuum cups are used. All these characteristics result in a modular robot, easy to control, very robust, and the grasping/weight can drastically increased the ratio to make possible specific surface travelling (Fig. 11(b)).

The robot's movement sequence to move in a horizontal direction is illustrated in Fig. 12 and summarised in the following steps:

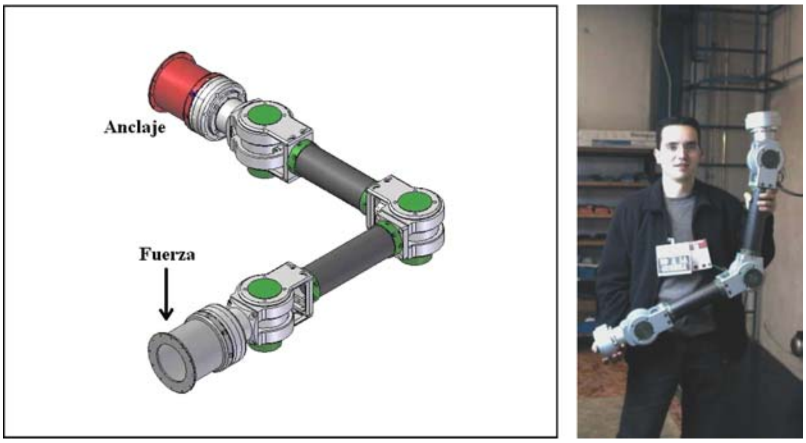
(a) Release the vacuum cups of the front platform.
(b) Elevation of the main body. Two joints are moved, at the same time, by only one electrical actuator, situated in the body and the movement is transmitted by a driving belt.
(c) Forward rotation of the front extremity, which is driven by a pneumatic cylinder.
(d) Lowering the body until the front platform touches the beam.
(e) Freeing the vacuum cups of the rear platform.
(f) Elevation of the main body, again, and freeing the rare extremity.
(g) Forward rotation of the rear extremity, which is driven by another pneumatic cylinder.
(h) Lowering the body until the rear platform touches the beam.

The movement's sequence required to transit from the horizontal to the vertical plane is simpler than the one described for the ROMA I robot. Knowing the distance between the robot and the wall, which is measured by the on-board laser telemeter, two joints of the robot are rotated simultaneously until the front platform is parallel to the face of the column. The pneumatic cylinder pushes the platform against the wall to allow the vacuum cups to stick to the surface. Once the front robot is fixed to the wall the rear platform is then released and the robot body is moved closer to the wall (Fig. 12).

The robot can change the direction of movement in the horizontal plane through a very simple sequence of movements. The body of the robot is elevated, leaving the rear extremity free. Next, the robot rotates around the vertical axis of the front extremity fixed to the original position. Subsequently, both extremities are extended and the robot's body is lowered until the free platform touches the target new direction.

4.3. *MATS Robot*

The MATS robot has an innovative climbing method (Balaguer et al., 2003b). It uses the special devices located in the environment (walls, tables, chair) that allow the robot to attach itself to the environment. This device, called *Docking Stations* (DS), has a conical male form that assembles with the robot's *Docking Mechanism* (DM) that has a conical female form. For this reason the robot moves along the environment by transiting from one DS to another. The main difficulty of



(a) (b)

Figure 13. MATS robot: (a) kinematics structure and (b) picture in an indoor environment.

this motion is the assembly procedure that must be performed with a small tolerance. The conical form of the DS and DM, with some conical parts, absorbs big part of the positioning and orientation errors during the assembly process. The mobility of the MATS robot is pre-defined by DS locations.

MATS robot has 5 DOF and is inspired in the symmetrical criterion (Fig. 13(a)). The robot must work in the same way when it has attached one tip or the other one. This number of DOF guarantees enough robot mobility in 3D environments, i.e. transitions from one wall to another (commonly vertical and perpendicular one respect to the other) and transitions from the floor to the walls are performed in an easy way. Its maximum area of work is 1.3 m and its maximum payload is about 2 kg.

One of the most important features of this climbing robot is its very light weight. The overall weight is about 11 kg, includig the motors' amplifiers, the main control unit and the wireless communication system. The relation weight/length (7.7 kg/m) is excellent having in mind that all the control hardware is on-board. It is easy to be handled by users or specialized personnel (Fig. 13(b)). The robot is totally autonomous and needs only the 24 VDC power supply from the DS.

The main reason for a so lighter robot is the use of an advanced actuator's technology based on the torque motors. Its main advantage is a constant high torque for a big range of velocities, including small ones. It has many other advantages with respect to the conventional brushless motors: significant reduction of the length of the motor (more than twice), significant reduction of the weight (about twice), and possibility to custom manufacturing of the light weight hollow rotor axis. All these advantages result in the reduction of the overall weight, of each axis, in more than three times. The same statement can be done for the length of the set gearbox-motor-brake-encoder, where ultra flat Harmonic Drive © devices are used.

The MATS robot has very good mobility features for 3D environment travel. Figure 14 shows the sequence of the robot's possible motions in a 3D environment. First, the robot is attached only to DS 1(a). In the second picture (b) the robot moves to dock (to attach) to DS 2. In this position the robot is firmly attached to both DS. The next movement (c) consists of disassembling (unattached) one tip from DS 1 and it freely moves from DS2. In the next position (d) the robot again is attached to both DS 2 and 3. And finally (e), the robot is attached only to DS 3 and freely moves in the environment. In this way it is possible to generate any transition between any planes.

5. Conclusions

This paper presents the general theory of the non-conventional climbing robots able to move between complex 3D environments. This type of robots is able to travel in all spatial directions and planes to perform inspection and maintenance operations of infrastructures, such as: bridges, skeletons of buildings, off-shore platforms, etc. The quality of its mobility must not be affected by the gravity force and at the same time the secure grasping must be guaranteed at any time. During

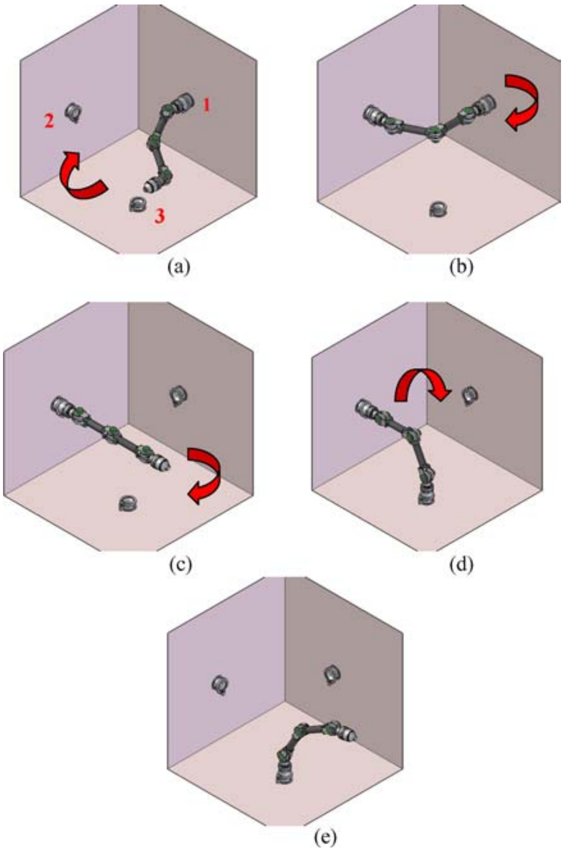


Figure 14. Motion sequence of the MATS robot during the transition among different docking stations.

the design of climbing robots, an important compromise will be reached: high robot mobility which leads to a high number of degrees of freedom, and, on the other hand, light weight due the fact that the robot is self-supported. To achieve this goal, several criteria must be introduced: mobility, symmetry, maximization of the gait.

The described general theory of climbing robots has been focused in several examples of robots developed by the authors during the last years. The 3D mobility of the ROMA I, ROMA II and MATS climbing robots had been described in detail. Several motion and gait generation strategies were also presented.

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