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Research article

Development of an industrial pipeline inspection robot

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Abstract

Purpose – The purpose of this paper is to describe design and development of a pole climbing robot (PCR) for inspection of industrial size pipelines. Nowadays, non-destructive testing (NDT) methods are performed by dextrous technicians across high-level pipes, frequently carrying dangerous chemicals. This paper reports development of a PCR that can perform *in situ* manipulation for NDT tests.

Design/methodology/approach – Introduces a PCR including a novel four-degrees of freedom climbing serial mechanism with the nearly optimal workspace and weight, unique V-shaped grippers and a fast rotational mechanism around the pole axis. Simplicity, safety, minimum weight, and manipulability were concerned in the design process.

Findings – The developed prototype proved possibility of application of PCRs for NDT inspection on elevated structures. Design and development of PCRs which are able to pass bends and T-junctions faces much more difficulties than those which should climb from a straight pole.

Practical implications – The robot is successfully tested on an industrial size structure (exterior diameter of 219 mm) with bends and T-junctions.

Originality/value – Design and development of a novel pole climbing and manipulating robot for inspection of industrial size pipelines. The robot is able to pass bends and T-junctions. The V-shaped grippers offer many advantages including safety and tolerance to power failure. After grasping the structure, in case of power failure in any of the grippers' motors, the robot does not slip on the structure. The *Z*-axis rotational mechanism provides fast navigation around the pole which is not possible with the traditional serial articulated arms.

Keywords Robotics, Pipelines, Inspection, Non-destructive testing

Paper type Research paper

1. Introduction

Pole climbing robots (PCRs) have many applications in the inspection of human made 3D tubular structures. One of the most important applications is performing periodical inspections with non-destructive testing (NDT) probes in order to asses the progression of material degradation and the detection of welding defects. Nowadays, NDT methods are performed by dextrous technicians across high-level pipes, frequently carrying dangerous chemicals. This task is extremely difficult and can be categorized as a dirty, dangerous, and difficult job. In the USA, wages for 3D occupations can be over USD70,000 annually and even though there are lack of workers for these jobs since they are dangerous for human life. Climbing robots with the ability of climbing across 3D tubular structures with bends and branches and scanning the whole or part of the pipe's surface, may be equipped with NDT probes and be used to do such inspections automatically.

As a result of the increasing interest on climbing robots all around the world, different types of climbing robots were developed for climbing over flat or curved surfaces. For holding robot attached to a smooth surface, suction cups (Dulimarta and Tummala, 2002; Nagakubo and Hirose, 1994; Ryu *et al.*, 2001; Yan *et al.*, 1999) or attraction force generated by propeller (Nishi, 1991, 1996) or magnets (Grieco *et al.*, 1998; Hirose *et al.*, 1991) were used. Robots whose end-effectors match engineered features of the environment like fences or porous materials or bars (Bevly *et al.*, 2000; Xu *et al.*, 1994; Yim *et al.*, 2001; Amano *et al.*, 2001) were developed. Robots for climbing inside pipes or ducts (Neubauer, 1994; Rossmann and Pfeiffer, 1997) or climbing across poles (Balaguer *et al.*, 2000; Almonacid *et al.*, 2003; Ripin *et al.*, 2000; Tavakoli *et al.*, 2005; Baghani *et al.*, 2005; Vossoughi *et al.*, 2004; Haynes *et al.*, 2009) were also developed. The later group is called PCRs.

3DCLIMBER is an industrial size PCR developed in the University of Coimbra (Tavakoli *et al.*, 2008b). The user requirement of the project defined the main objectives as:

- ability to autonomously climb industrial pipes with bends and T-junctions;
- ability of manipulation on the structure without the need of an extra arm; and
- workspace and weight optimization, simplicity, and safety should be concerned in the design process.

None of the already developed robots could fulfill the user requirements mentioned before. They were either not able to pass bend section of up to 90° (Baghani *et al.*, 2005; Hosokai and Hara, 2001; Ripin *et al.*, 2000; Vossoughi *et al.*, 2004) or were not able to pass branches (Almonacid *et al.*, 2003).

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The most recently reported PCR is a quadrupedal robot which can rapidly climb across straight poles (Haynes *et al.*, 2009), but the ability of passing the bent sections and T-junctions was not reported. Furthermore, this robot may not be able to climb from metallic surfaces due to the claws-like grippers which are designed for soft materials, like wood.

Previously developed PCRs were based on either continuous or step-by-step based climbing mechanisms. Continuous motion PCRs (Baghani *et al.*, 2005; Hosokai and Hara, 2001) which use tires both for climbing and gripping purposes are faster and lighter than step-by-step motion PCRs. Their main drawback is the lack of maneuverability. These kind of robots are mostly appropriate for climbing across simple poles and performing simple tasks. A sample application is washing straight poles without bends and branches. On the other hand, if a robot aims to perform more complicated tasks, like welding, testing or painting pipes, a step-by-step based design is a better choice. The reason is that this type of PCR may take advantage of a separate gripping module which makes the robot more stable on the pole. Also, it has a separate climbing module which can be used for manipulation and performing complicated tasks. The selection of an optimized design highly depends on the application. It is obvious that using a step-by-step mechanism for washing poles is possible but it is not the best solution. Additionally, step-by-step based design, several climbing structure configurations can be considered with namely: serial, parallel or hybrid mechanisms. Each of the mentioned mechanisms have some advantages and disadvantages when compared to another. The climbing configuration is an important issue which is highly related to the considered applications for the robot. Almonacid *et al.* (2003) have developed a six-degrees of freedom (DOF) parallel robot with pneumatic actuators Balaguer *et al.* (2000) developed a six-DOF serial climbing robot for inspection of 3D complex environments. Tavakoli *et al.* (2005) developed a hybrid (serial-parallel) mechanism using electrical cylinders. One of these robots was reported to be able to pass bends and branches (Balaguer *et al.*, 2000), but it is massive (75 kg) due to the excessive number of DOF. The study of the previously developed PCRs helped to categorize PCRs and study the advantages and disadvantages of each group in the conceptual design phase of the current project and consequently to introduce a benchmark for evaluation of PCRs performance (Tavakoli *et al.*, 2008a).

On the other hand, as PCRs should take their own weight up during climbing, it is very important to optimize the design of the dedicated mechanisms with the objective of minimizing the overall weight of the robot. Based on this fact, a designer should consider optimization in all steps of the design process to reduce the weight and the size of the robot as much as possible. The most significant optimization step takes place during the conceptual design. In this phase, the best mechanism with minimum DOF able to perform the proposed tasks without including redundant capabilities was selected. Redundant DOF make the robot heavier without necessarily increasing the robot abilities for performing a given task.

Designing the robot with minimum DOF as well as eliminating the necessity for an additional arm, would reduce the weight and complexity level of the robot, but at the same time it increases the level of complexity of the design since that limits the design choices.

In this paper, we address the problem of designing a mechanism with minimum DOF which can climb over 3D structures with bends and branches. Then we describe the detailed design of the robot and discuss its performance based on test results of the developed prototype.

2. Concept

As stated, optimal design was concerned in all phases of the design. The most significant optimization takes place in the conceptual design phase. In this phase, the most appropriate mechanism for the desired objectives of the project should be selected. A well designed climbing structure with minimum DOF will result in a lighter, simpler and more efficient robot.

2.1 Design categories

All of the previously developed PCRs were categorized in four groups:

1 Continuous motion PCRs.
2 Step-by-step based PCRs with serial structure.
3 Step-by-step based PCRs with parallel structure.
4 Step-by-step based PCRs with hybrid structure (serial-parallel mechanism).

In a previous publication (Tavakoli *et al.*, 2006), these categories were evaluated in terms of ability of passing bends, ability of passing branches, climbing speed, fault tolerance (in case of power failure for instance), operating workspace and maneuverability, payload to weight ratio, simplicity, and modularity. This evaluation was based on the performance of the previously developed robots. For instance, it is well known that generally parallel mechanism benefits from a better payload to weight ratio compared to serial mechanisms, but they have smaller workspace and therefore deficient maneuverability. On the other hand parameters like the ability of passing branches, climbing speed, simplicity, modularity, and fault tolerance were judged according to the previously developed PCRs.

Continuous motion PCRs, use wheels both for climbing and gripping. Therefore, compared to step-by-step based designs, they are less complex and faster, but on the other hand less tolerant to faults and due to their encircling gripper design, unable to pass branches. A final evaluation of each PCR design was weighted by the reference of each parameter for the application envisaged and thus for example the best choice for a PCR for cleaning a pole may not be the best choice for NDT operation on a pole. If the robot is considered for cleaning a straight pole, passing bends, and branches has no effect and is weighted zero on the evaluation, while for the objectives of 3DCLIMBER, passing bends and branches has a high impact and is highly weighted.

The result of this analysis showed that a step-by-step based PCR with serial structure conforms more than other design categories with the objectives of the 3DCLIMBER user requirements (Tavakoli *et al.*, 2006).

2.2 Minimum DOF for climbing across 3D structures

To design the climbing mechanism with minimum DOF a survey was performed in order to study the necessary DOF for climbing and manipulating over 3D structures. Figure 1 shows a step-by-step based PCR climbing along the straight part of a pole. As can be seen from the figure, one DOF is sufficient to perform this task.

Figure 1 Climbing along pole

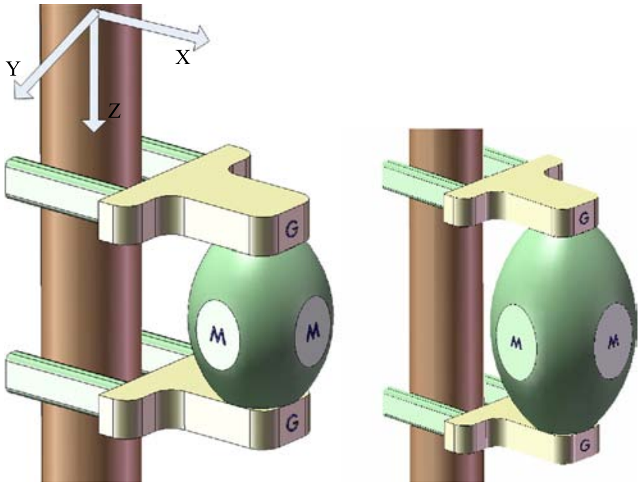


Figure 2 shows a PCR passing a bend. It required two additional DOF: one rotation in order to overcome the bend and another translation to move the upper gripper to the straight section after the bend.

But if the robot is not aligned with the desired *XZ* plane in poles containing T-junctions, then an additional rotation is necessary in order to align the robot with the next straight target segment (Figure 3).

The latter DOF is also necessary for performing NDT tests as the robot's manipulator should be able to scan every point on the structure. The combination of the above four-DOF provides the necessary manipulability not only to reach to every point on the structure, but also to perform necessary operations after reaching target point on pole.

3. Climbing structure: design and analysis

3.1 Design

As the analysis in the previous section showed a serial mechanism with four-DOF (two translations and two rotations) is required to climb across 3D tubular structures. A dedicated serial mechanism providing the required DOF was designed. As stated earlier, one of the reasons for choosing serial configuration as climbing mechanism is to increase workspace and manipulability which is a key factor for a multi purpose robot. The designed climbing module consists of a three-DOF planar serial arm and a *Z*-axis rotating mechanism (Figure 4). Combining the three-DOF arm with the rotating mechanism provides two rotations and two translations on the manipulator in relation with the base, which are necessary to achieve the design objectives as explained previously. The rotating mechanism which is designed in a different way from traditional serial arms is not only necessary for orienting the robot for appropriate bend section but also to significantly increase the manipulability of the robot as in this case the robot can rapidly rotate around the pole axis and scan its surface. This choice also increases significantly the workspace of the robot.

Figure 2 Overtaking bent section

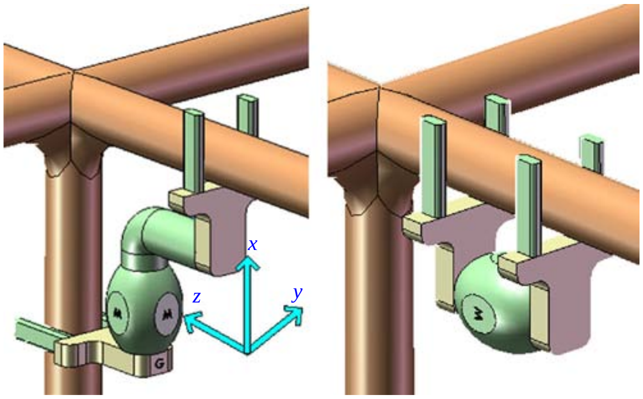
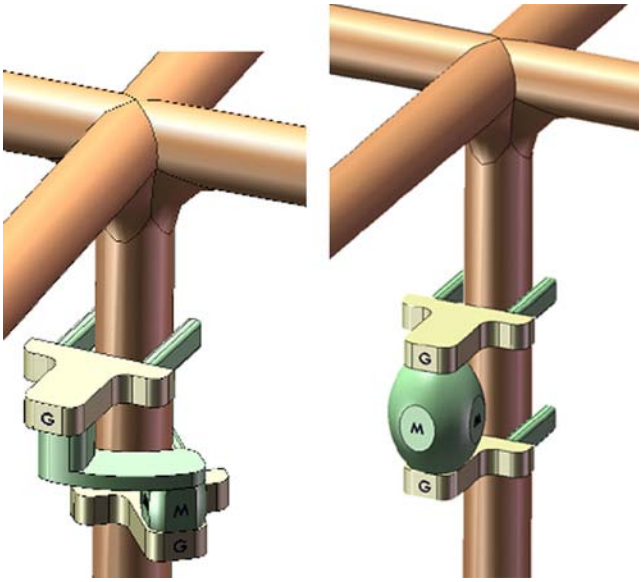


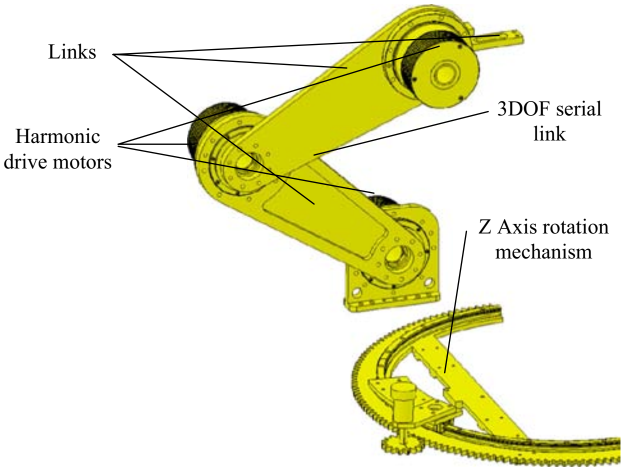
Figure 3 Rotating around pole



3.2 Kinematics, dynamics, and workspace analysis

In order to calculate the length of the links, the required torque for each joint and also in order to select the appropriate actuators, the kinematics, workspace, and dynamics analysis of the arm were performed using recursive Newton-Euler

Figure 4 Four-DOFs climbing structure



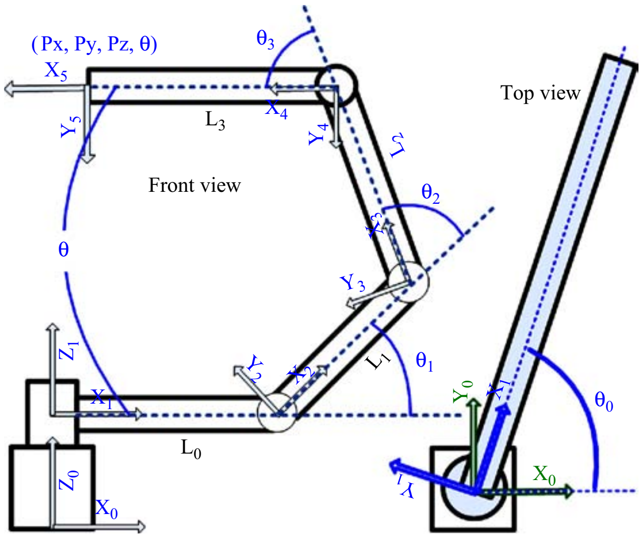
formulation (Craig, 1989). This process is briefly described in this section in order to clarify the design process. Figure 5 shows a simplified model of a serial four-DOF mechanism. In this model, the rotational guide is replaced with a simple link in order to simplify the kinematics and workspace analysis. Using the direct and inverse kinematics equations of this model, Jacobean matrix was also obtained. Afterward using some geometrical analysis and algorithms which will be described later, nearly optimal length for the links were calculated. Considering the links' length and dynamic analysis equations, the required torque for each joint was calculated and appropriate actuators were selected. To validate the design, the robot model was developed in SolidWorks and simulated in COSMOSMotion package. Some routines were developed to generate trajectories for each joint so that the robot can travel along a straight line or pass a bend section with a specific bend angle. Then the generated trajectories were used by the simulation engine. Simulations showed that the robot is able to pass bend sections of 90° with the calculated link lengths and actuators. Figure 6 shows some snapshots from simulation of the robot model.

3.3 Length of the links

The length of the links affects the workspace and the demanded torque of the serial mechanism. Lengthier links may not only construct a bigger workspace, but it also increases the demanded torque by the joints. The length of the links should be calculated with the objective of reaching a more efficient workspace and not a necessarily a bigger workspace. A more efficient workspace can be obtained when the required workspace (the workspace which make the arm able to pass bends of up to 90°) coincides with the robot workspace. Analytical and geometrical analysis were performed to increase the workspace efficiency. This analysis led to two specific formulas between the design parameters which will be presented.

Figure 7 shows the schematics of the 3DCLIMBER climbing mechanism when climbing a structure. l_1, l_2, and l_3 are the length of the climbing arm links, D is the diameter of the Z-axis rotating mechanism guide, and d is the diameter of the pole. The concentric circles show the constant workspace of the serial mechanism considering $\theta = 180°$ (θ is the angle between the manipulator and the base of the robot as can be seen in Figure 5). The exterior radius of the circles is equal to $l_1 + l_2$ and the interior radius is equal to $|l_1 - l_2|$. If the third link is not considered in the workspace analysis, the center of these concentric circles would locate on "O" (Figure 7). However, the third link transfers the center from "O" to "C" equal by the length of the links (l_3).

Figure 5 Simplified model of the four-DOF mechanism



To have the maximum straight step size, which is the robot's thrust on the pole in each step:

1. "$l_1 + l_2$" is the diameter of the exterior workspace circle and determines the maximum thrust of the robot and thus should be as big as possible.
2. For the maximum thrust, the difference between the minimum and maximum distances of the manipulator and the base should be maximized. This means that the minimum distance ($S_{\min}$ in Figure 8) should be as small as possible and the maximum distance ($S_{\max}$ in Figure 8) should be as big as possible.

While the first condition is to enlarge the workspace of the robot, the second condition tries to make the workspace as efficient as possible. Enlarging the workspace as suggested by the first condition increases other costs like the weight, required torque and size, while the second condition decreases such costs. To fulfill the second condition, the vertical diameter of the concentric circles of the workspace should coincide with the axis of the pole. In this way, the maximum thrust would be possible. To do this, the $l_3 = D/2$ condition should be fulfilled (Figure 8).

The minimum and maximum distance between the base and the manipulator is also shown in Figure 8. To make the thrust bigger, ($S_{\min}$) should be minimized. To do this, the radius of the internal circle of the workspace should be zero. This leads to the condition $l_1 = l_2$ which is shown in Figure 9.

To maximize the thrust on the X-direction which is necessary for passing the 90° bend sections, the vertical distance S_v (Figure 10) should be minimum. As it can be seen in Figure 10, the maximum possible X thrust happens at the horizontal diameter of the workspace's circle. Thus, by minimizing the S_v, workspace circles shift toward the Z-axis direction and consequently the thrust on the X-direction increases. To minimize S_v, $S_{\min}$ should be minimized, which is indeed the same condition which has been discussed previously ($l_1 = l_2$).

Therefore, in order to maximize the thrust, the following three conditions were considered in the detailed design phase:

1. $l_1 + l_2$ should be maximized within the limits of the robot's weight and the joint required torques;
2. $|l_3 - (D/2)|$ should be minimized or in the optimal condition should be zero; and
3. $|l_1 - l_2|$ should be minimized or in the optimal condition should be zero.

The numerical values for the length of the links was obtained in the detailed design phase by considering the mentioned conditions using the algorithm which is shown in Figure 11. According to this algorithm, the second and the third conditions are considered for selection of a sample length for the links. In this way, a value for l_3 was obtained close to the radius of the Z-axis rotation mechanism guide and $l_1 = l_2$ was also considered. It should be mentioned that considering the diameter of the structure and other design restrictions,

Figure 6 Sample snapshots of simulated motion of the robot model

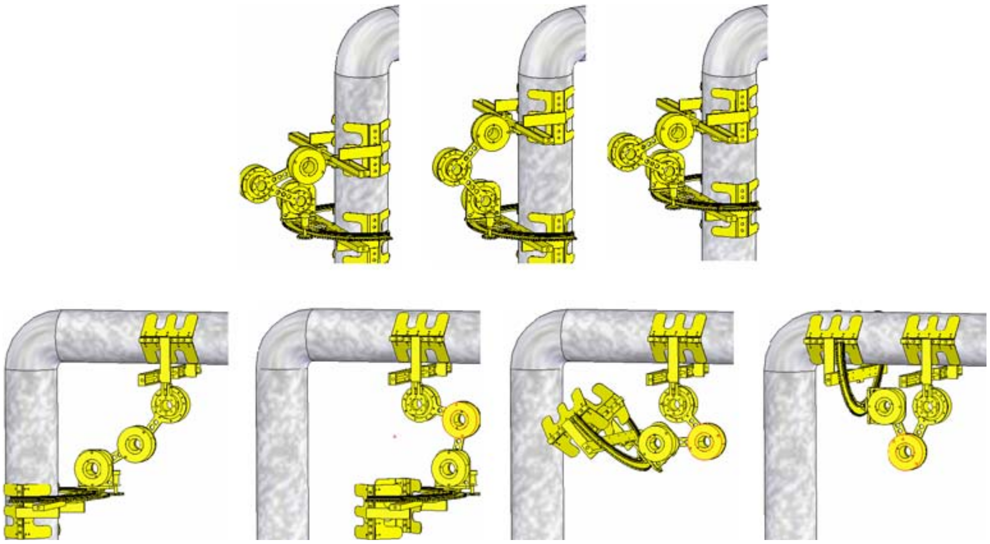
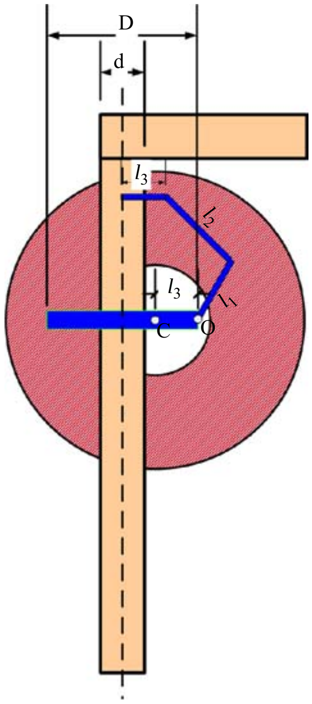
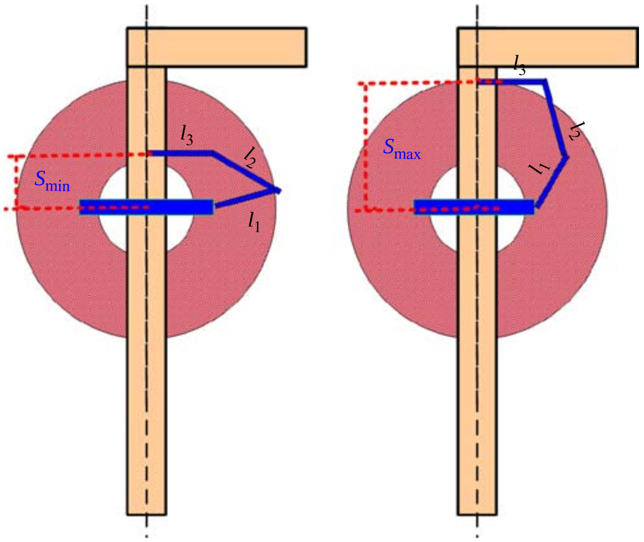


Figure 7 The constant workspace of the articulated three-DOF arm



the Z-axis rotation guide had been previously chosen from the commercially available guides with a diameter of $\phi = 600$ mm. Finally, the maximum value for l_1 and l_2 was obtained considering the torque limitation of the motors. As a result of the algorithm and also other design constraints, the following values for the workspace analysis were obtained: $[l_0, l_1, l_2, l_3] = [300,220,220,350]$ (all in mm); When the 3DCLIMBER climbs over 3D structures, most of the time it has a constant θ angle. θ is the angle between manipulator and base of the robot. For climbing across the straight pole, the angle is always $\theta = 180°$ and for passing bends, θ is the same as the bent angle (for a bent angle of 90°, $\theta = 90°$).

Figure 8 If $l_3 = (D/2)$, the vertical diameter of the concentric circles coincides with the axis of the pole



A MATLAB script was developed for workspace analysis of the mechanism considering all of the limits of the joints. The results of the constant workspace analysis for $\theta = 180°$ and $\theta = 90°$ is shown in Figures 12 and 13.

4. Detailed design, development, and control

The proposed PCR consists of two main parts: a four-DOF climbing module and two gripping modules. While one of the grippers grasps the structure, the other gripper can manipulate around the structure. The fixed gripper is called "base of the robot" and the moving gripper is called "manipulator." At each climbing step, these grippers switch their role once (as base or manipulator).

One of the grippers is attached to a manipulator, and the other one is attached to the base of a rotating platform. This configuration provides four-DOF between grippers, allowing

Figure 9 The condition $l_1 = l_2$ helps increasing the thrust of the articulated arm

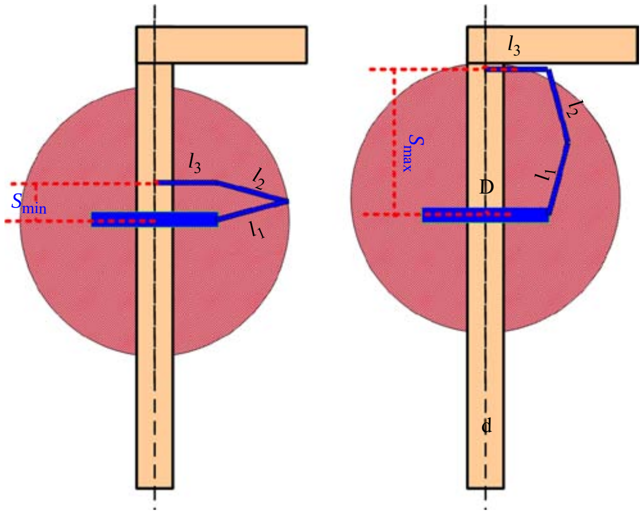


Figure 10 The condition $l_1 = l_2$ minimizes the D_v, which indeed maximizes the arm thrust in X (bent section) direction

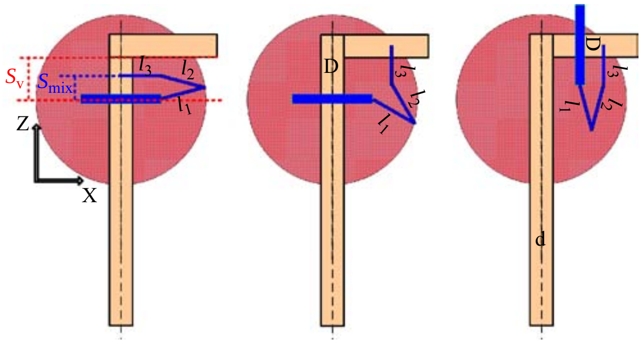
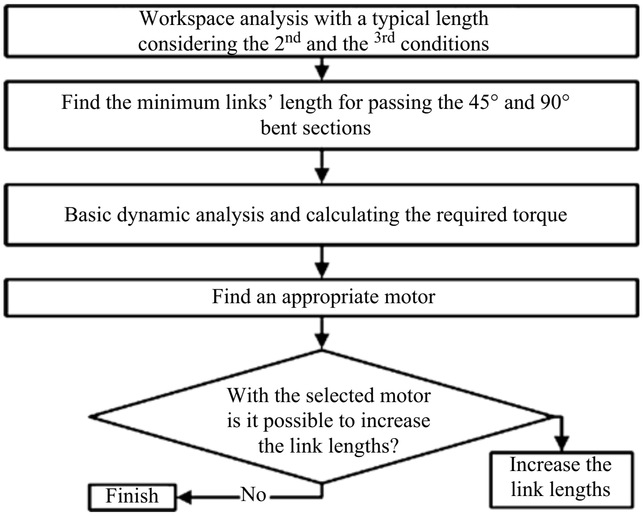


Figure 11 Algorithms for calculating the links' length



the movement along poles with different cross sections and geometric configurations. Weight optimization was considered in the design of all of the robot's non-standard parts as the weight is a very important factor in climbing robots. All non-standard parts were designed and manufactured with 7075-T6 aluminum. This type of aluminum is heavily alloyed with zinc and has an ultimate tensile strength of 510-538 MPa providing a high strength to weight ratio.

4.1 Grippers

Each gripper consists of two unique multi-fingered V-shaped bodies, a brushless motor driving one right hand and another left hand ball screws through two linear guides. The V-shaped grippers have mechanical self centering properties reducing significantly the control efforts for precise positioning of the robot's grippers, in order to assure safe gripping (Figure 14). To design the grippers following items have been considered:

- Each gripper should be able to withstand the total torque generated by the robot weight and by the motors' reaction torques. Therefore, when one of the grippers is attached to the pole the other gripper can freely detach from the pole in order to manipulate over the pole and perform some tests on the structure. This ability eliminates the need for an extra manipulating arm and therefore significantly increases the maneuverability of the robot.
- Grippers should be able to operate in a range of pole diameters and not only a specific diameter.
- To increase the safety, the gearbox ratio and ball screw pitch should be calculated in a way that after the gripper grasp the structure, the robot can stay attached to the pole even if there is a power failure.

V-shaped part of the gripper is designed long enough (250 mm), so that they can fulfill the first requirement.

For the second requirement, the linear guides of the gripper were designed long enough so that it can grasp structures within the diameters of 200-350 mm.

In order to increase the friction between the pole and the gripper and consequently to increase the safety of the system, grippers are covered with rubber. Each gripper is actuated by a 50 W Maxon brushless DC motor coupled with a planetary gearbox which can apply 5 Nm torque. The motor is coupled with a THK ball screw with 2 mm pitch. In this way, the gripper can exert forces up to 1,000 N. When the gripper is opening, the motor is controlled by position. When the gripper is closing torque control is applied to the motor in order to control the amount of the force applied by gripper. The small pitch of the ball screw along with the high ratio of the planetary gearbox increases the inertia at the motor shaft, so that after the gripper grasps the structure it can be stayed attach to the structure even if the motor is not powered. This ensures the third requirement.

4.2 Climbing structure

The climbing structure previously described was implemented with the following elements:

- A three-DOF serial link that includes three Harmonic Drive AC brushless motors coupled with 160:1 Harmonic Drive gearbox, capable of generating torques up to 260 Nm (LLC, 2008). Harmonic Drive gearboxes are lighter, more precise and more efficient than other types of gearboxes. Figure 15 shows the four-DOF climbing structure.

Figure 12 Different views of the constant orientation workspace for $\theta = 90°$, dimensions in mm

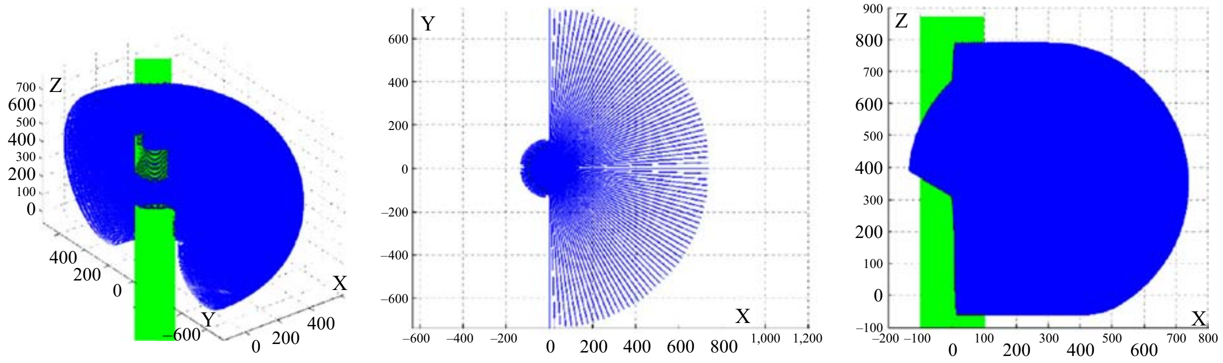


Figure 13 Different views of the constant orientation workspace for $\theta = 180°$, dimensions in mm

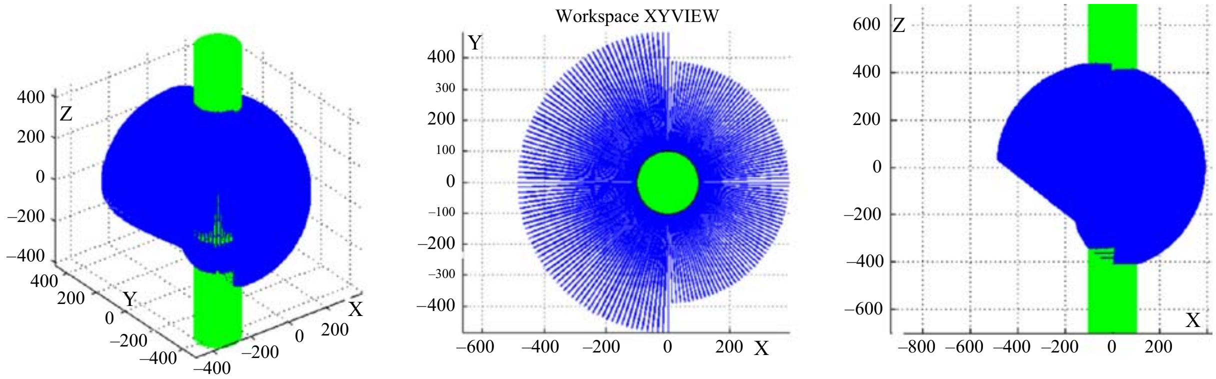


Figure 14 Gripper of the 3DCLIMBER robot

- A rotation mechanism around the axis of the structure which consists of a THK rotation guide and slider, gearing mate and a Maxon brushless DC motor. This rotation mechanisms provides a fast motion around the structure axis, which is necessary for performing most of the inspection tasks like welding inspection. Table I shows the main characteristics of the robot.

4.3 Structural optimization of the parts

Weight optimization was considered as an important issue in all design phases including selection of the mechanism and also to calculate length of the links. This was also considered in design of robots links and parts. Many parts of the 3DCLIMBER are custom design and should be manufactured. The classical approach for structural analysis

Figure 15 The four-DOF climbing mechanism

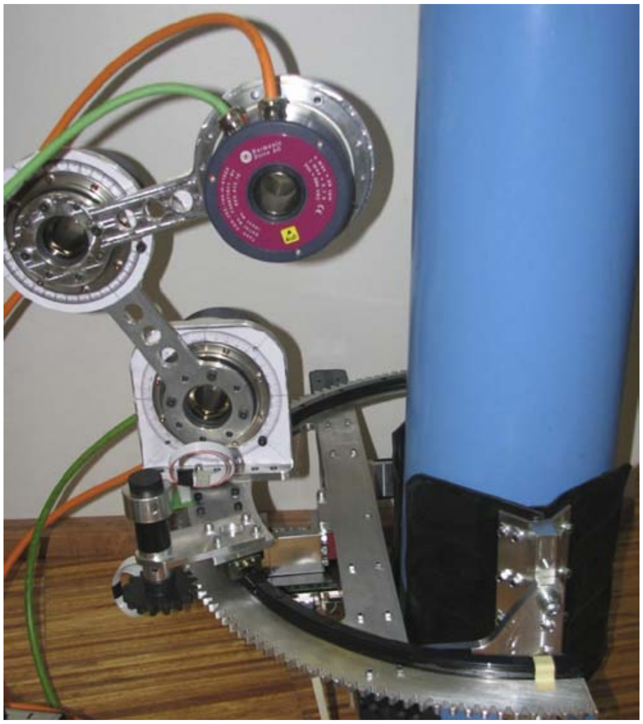


Table I Main characteristics of the robot

DOF	4
Quantity of motors	6
Climbing procedure	Step-by-step
Weight (kg)	42
Material of the parts	Aluminium 7075-T6
Robot size (m)	0.5 × 0.6 × 0.5
Extended robot size (m)	0.5 × 0.6 × 0.85
Climbing speed (m/min)	1.0
Minimum diameter of the pole that gripper is able to grasp	200 mm
Maximum diameter of the pole that gripper is able to grasp	350 mm

is to first estimate forces and torques that the part should withstand and then consider a safety factor. After that one should design the parts so that it fulfill the safety factor. This guarantees the safe operation of the part. On the other hand, when a part is under load, the stress is not distributed equally in all volume of the part. Minimum-weight structural designs have been developed for various types of behavior specifications including stiffness, elastic and plastic strength, and stability. Computer aided structural analysis helps to demonstrate stress and strain analysis and safety factor distribution of a part subject to loads and moments. Using such tools, one can redesign a part several times to reach the nearly minimum possible weight. To achieve the minimum-weight structural designs, one should try to decrease the variance of the safety factor distribution. Many techniques and method were developed during last decades for optimum structural design such as genetic algorithms-based optimization but these methods have some limitations. For instance, they do not consider the manufacturing limitations or costs. Using finite element structural analysis software, one can redesign a part several times to reach the near optimal structure, while considering the limitations on manufacturing and costs. This method was applied in design of all non-standard and non-commercial parts of the 3DCLIMBER. COSMOSMotion engine which is a plug in for SolidWorks was used as the finite elements analysis tool. Also the deflection should be less than a certain value which is the maximum permissible deflection value. This value which depends on many factors including the material and the permissible geometrical deflection of the part due to restriction related to the whole mechanism design. The maximum permissible deflection of the gripper arm was considered 0.2 mm. After several redesigns of parts some of the parts decreased their weight to one-third of their initial design weight and the overall weight of the robot was decreased about 30 percent. Figure 16 shows the safety factor distribution and deflection in some of the parts. The minimum safety factor is 3, but the design is optimized as much as the geometrical design parameters and also manufacturing limitations were allowing.

5. Control

5.1 Sensors

Two types of sensors are used in the grippers. Four force sensitive resistors (FSR) are attached to each side of each gripper (a total of 16 FSR sensors are used – Figures 17 and 18) in order to measure the force on different locations, providing not only information about the amount of force exerted, but also information about the force distribution on the grippers surface. Positioning error and angular deviation of the manipulator result in deficient gripping and thus FSR sensors of the gripper report different values. In this case, an error will be reported to the user for further decision.

FSR sensors are also useful during the assembly and calibration of the gripper. Since both links of each gripper should be installed completely symmetric, the measured values provide an indication of possible misalignment.

On the other hand, FSR sensors are covered by compressible rubber and are not directly contacting the structure. Consequently, there exist lack of precision on their values. To overcome this problem, two strain gauges are glued to each gripper link. When the gripper grasps the pole, deflection of the links which is proportional to the applied force is measured by the strain gauges and consequently the grasping force of each gripper is calculated. When the grasping force reaches to a target value, the gripper's motor will stay powered to maintain the force. After integration of strain gauges which can measure the force more precisely than FSRs, FSR are only being used to report the force distribution on the gripper. In this case, when one gripper grasps the pole, all eight FSRs report a value. If the value reported by one or more than one of FSRs is very different with a pre-specified value, the error of "bad grasping" will be reported. In this case, the operator should find and solve this problem. Currently, we are working on integration of additional sensors and a self calibration system to address the "bad grasping" problem autonomously.

Other sensors were also used in the climbing and gripping mechanism, including encoders in the gripping, rotating and climbing mechanism actuators, optoelectronic sensors to provide the zero reference of the actuators in the start up process, and sharp range finder sensors for estimating the distance between the manipulator and the structure.

5.2 Control architecture

As shown in Figure 18, three AC brushless motor controllers, three DC brushless motor controllers, and a data acquisition module are used. AC motor drivers are SEW three-phase 1.4 kW driver with CANopen interface (SEW-EURODRIVE, 2009). DC motor drivers are fully digital intelligent servo drives from Technosoft (2009) with CANopen interface. These controllers can control motors in position, velocity or torque. All motors of the climbing structure (three AC motors and one DC motor for the *Z*-axis rotation) are controlled in position mode. The two DC motors used in the grippers are controlled in both torque (when closing) and position control modes (when opening). All the drivers are communicating through a CAN bus using the CANopen protocol. A CAN to universal serial bus (USB) module is used to connect the CAN bus to an PC that acts as low-level controller. The values from analog and digital sensors are acquired with USB data acquisition modules from national instrument.

5.3 Control software and algorithms

The user sends high-level control commands to the robot controller through the graphical user interface (GUI). The command can be "step forward," "step backward," "pass bend," etc. Then the control algorithm generates and sends

Figure 16 The structural analysis was performed for all custom designed parts with the objective of minimizing the weight of the parts and thus to minimize the over all weight of the robot

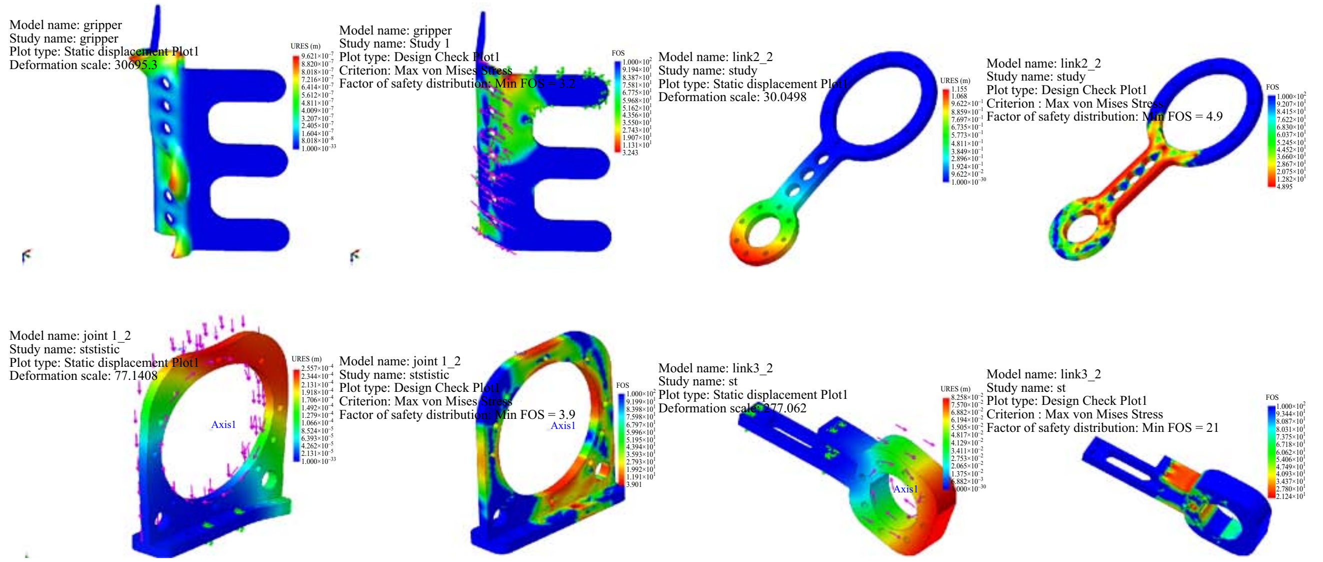


Figure 17 FSR sensors attached to a gripper

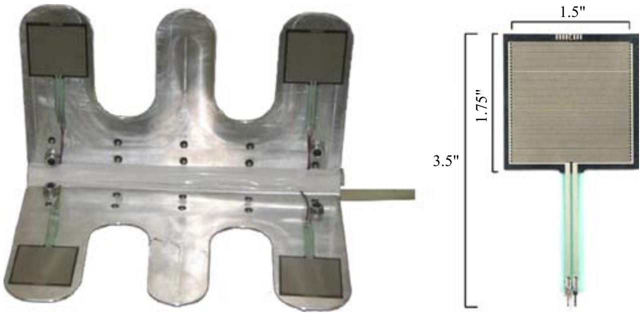
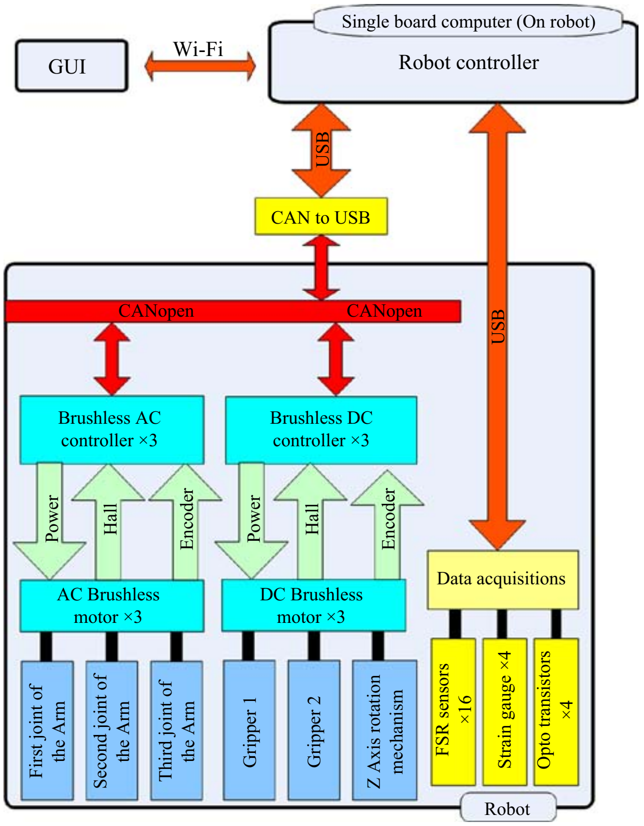


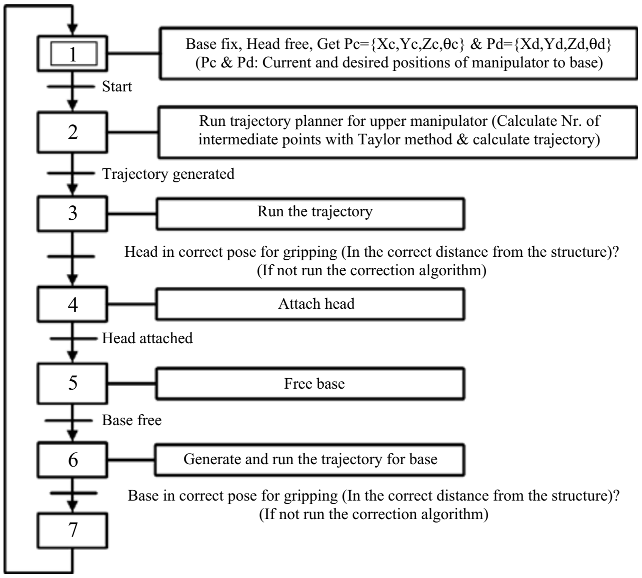
Figure 18 Electronics architecture of the 3DCLIMBER robot



the low-level control commands to the actuators. User can also define a mission. In this case, s/he should define the start point and the end point for the manipulator and then the path-planning algorithm calculates the number of straight steps or "passing bend" steps. In the current status of the robot a priori knowledge of the structure geometry is provided to the path-planning algorithm. For instance, a "step forward" command includes opening of the upper gripper, moving up the manipulator in a straight line, closing the upper gripper, opening the lower gripper, moving up the lower gripper, and closing the lower gripper. The "step forward" Grafcet is shown in Figure 19. Straight line manipulator trajectories are generated by the control algorithm using the Taylor (1979) method. Based on the Taylor straight line planning method, the algorithm calculates the minimum number of intermediate points between the poses which guarantees the required trajectory tracking precision. Accurate tracking of a straight line is important, because in this case the robot grippers open less and consequently the energy and the time for opening and closing of grippers will be saved. Figure 20 shows the generated trajectory for all joints to pass a 90° bent section.

Currently, we are integrating a system for absolute localization of the robot on the structure based an external infrared camera observer and infrared light-emitting diodes on the robot. Figure 21 shows a snapshot from the GUI application of the robot. This GUI is a part of an architecture developed for server-client based remote control of climbing robots generally and 3DCLIMBER specifically. This architecture includes a TCP/IP-based communication protocol.

Figure 19 One step motion across a straight pole



A single board computer is installed on the robot as the server. Commands are sent by the operator through GUI (based on client) and transferred to the robot's computer (server) (Figure 18).

6. Experimental results

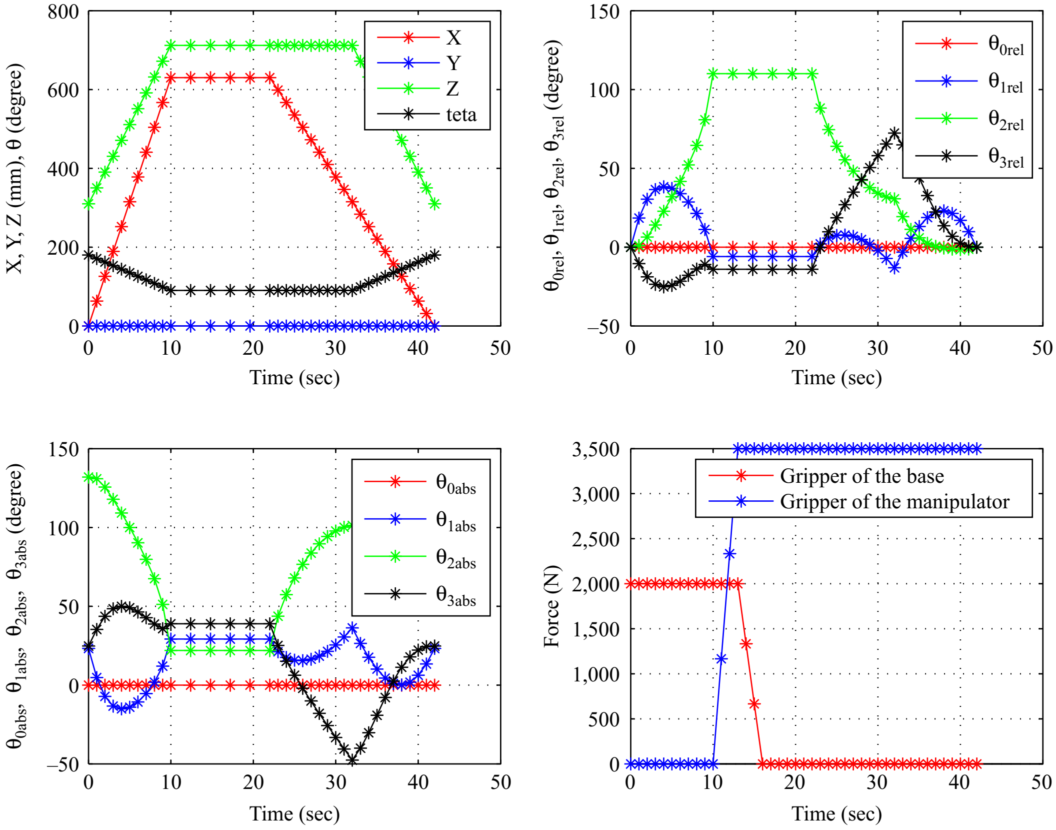
A structure was developed as a test environment of the robot which includes bends of 45 and 90° and a multi branch section (Figure 22). The structure has a diameter of 219 mm. The robot was successfully tested on the structure. Figure 23 shows some snapshots from the robot climbing across the structure.

Also a problem was revealed during the experiments, which we are currently working to address it. Our preliminary experiments showed that shortly after a gripper grasps the pole, it tends changing its tilt angle. This is due to the torques resulted by the weight of the robot. Therefore, the closed gripper does not stay perpendicular to the pole until end of the step (Figure 24(b)). Consequently, as the other gripper maintains the 180° with the first gripper, it will not be perpendicular to the pole. Therefore, a perfect gripping action cannot be established. It should be noted that it is usually a small error, but it accumulates in each step. To compensate this error, we are integrating four accelerometers (one on each link) to measure the tilt angle of the gripper. After achieving each step, the three-DOF arm will compensate the error so that the open gripper will stay perpendicular to the structure. Figure 24 shows an exaggerated representation of the problem and the proposed compensation method.

7. Conclusion and future works

Climbing and manipulation along 3D structures with bends and branches requires at least four-DOF. Therefore,

Figure 20 Trajectory of the joints and torque of the electrical actuators for passing a 90° bent section



Note: Here "abs" stands for absolute and "rel" stands for relative

Figure 21 Snapshots from the user interface of the climbing robot

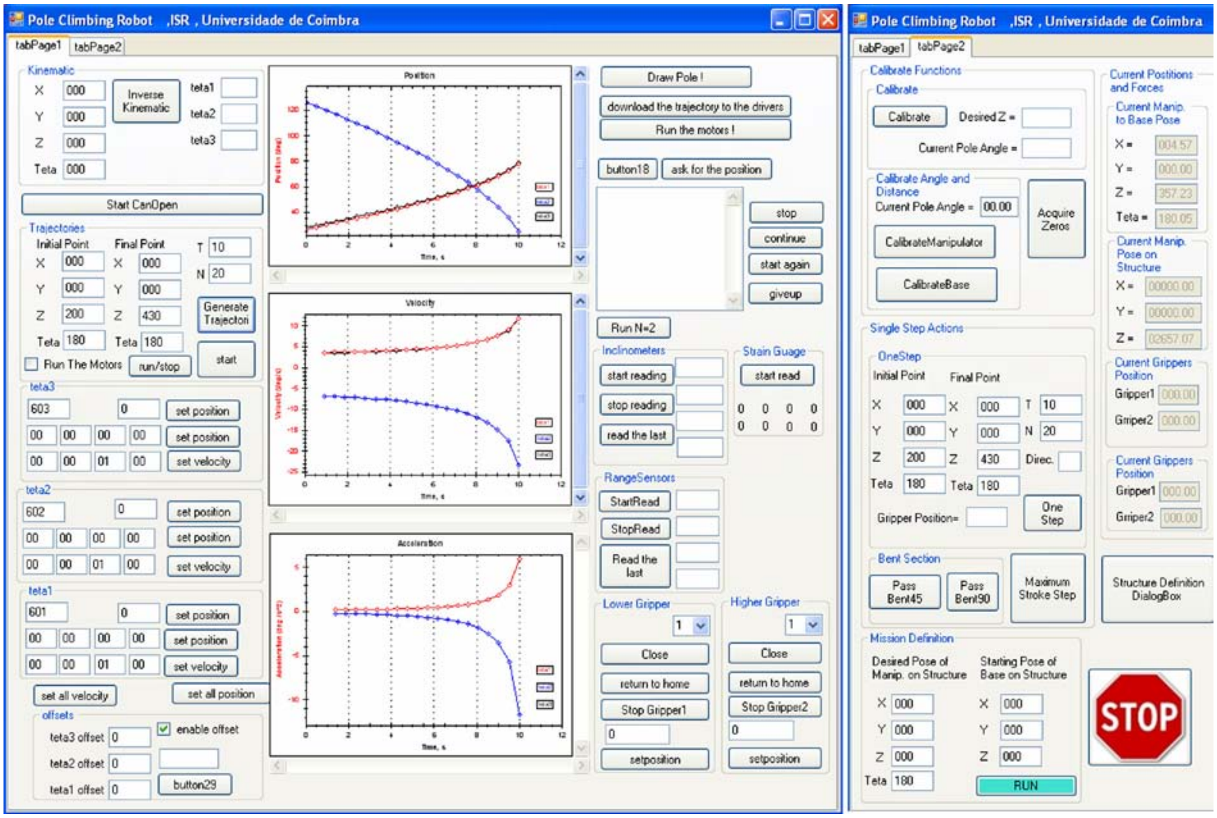


Figure 22 Developed structure for test of the PCR

a four-DOF serial mechanism was designed and developed as climbing structure of the 3DCLIMBER robot. Using the results from kinematics and workspace analysis, the detailed design of the robot was achieved and then validated using motion simulating and finite element analysis softwares. The robot was developed and successfully tested. During the experiments a problem related to placement of grippers was revealed. To address this problem, error compensation algorithm and accelerometers for measuring the absolute angle of links are being integrated.

Table I summarizes the characteristics of the robot. 3DCLIMBER can climb from structures with a minimum diameter of 200 mm to a maximum diameter of 350 mm. To change the minimum and maximum values, one may use spacers to easily shift these values to smaller or bigger diameters, but the range will be always equal to 150 mm. However, due to the modularity of the system, the gripper can be easily changed and thus different grippers for different structure sizes or with bigger or smaller operating ranges can be used without any change on the climbing and control mechanisms.

The main improvement of this robot in comparison with the previously developed PCRs is its greater maneuverability and safety. First of all, the specific Z-axis rotation mechanism, provides fast manipulation around the structure which is necessary for inspection purposes and furthermore facilitates and accelerates locating the climbing mechanism below a specific bent section in T-junctions. The second reason which increases the maneuverability and safety are grippers. Long V-shaped grippers with their high-inertia system (due to

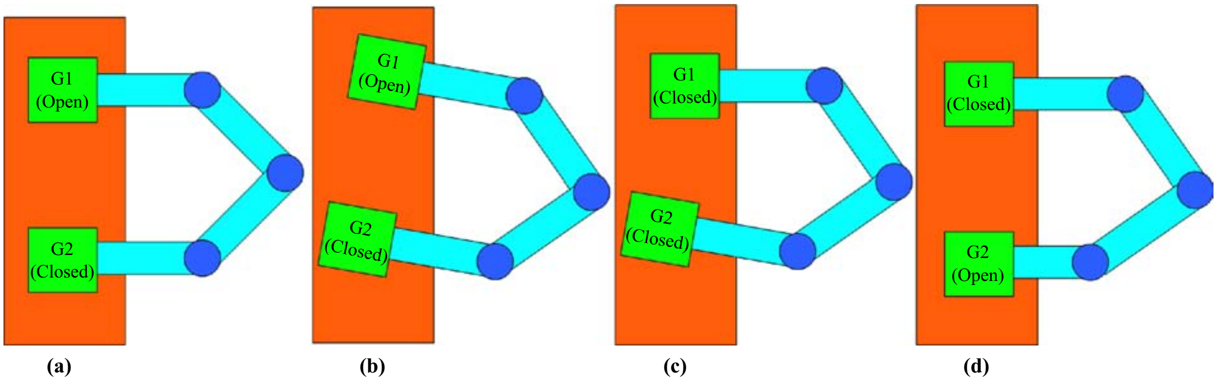
Figure 23 Sample snapshots of the experimental results

high-ratio gearbox and low-pitch ball screw of the rotation to linear transformation mechanism), allow the robot stay safely on the structure with only one of the grippers, while the other gripper can take the role of a manipulator and manipulates over the pole freely. Moreover, the grippers are tolerant to power failure meaning that they keep their last position in case of power failure without sliding on the structure.

Using serial mechanism as the climbing structure has the advantage of a large workspace which results in big climbing steps, good maneuverability and simple control. However, compared to parallel mechanism, the system becomes heavier.

In the current prototype, commercial drivers were utilized to drive actuators. Such drivers are massive due to excessive and unnecessary parts. Considering that the robot has three similar actuators and drivers, dedicated drivers avoiding the common and unnecessary parts will reduce the robot's weight. Future works include integration of an absolute localization system, integration of welding test probes and design and development of dedicated drivers for actuators.

Figure 24 Demonstration of the tilt angle error and compensation



Notes: (a) Correct status; (b) after occurrence of the error; (c) error compensation for the upper gripper; (d) error compensation for the lower gripper

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