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# ON THE DESIGN AND DEVELOPMENT OF CLIMBING AND WALKING ROBOTS FOR THE MARITIME INDUSTRIES

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### ABSTRACT

**Modern robotic systems are increasingly powerful in terms of sensor fusion and mobility. Present technological progress allows advanced robots to cope progressively much better also with complex environments such as those which are frequently found in the maritime industries. An overview of the development of mobile robots (climbing and walking) is presented with examples taken from some research projects carried out by the Industrial Automation Institute of the Spanish Council for Scientific Research.**

**Keywords**: Automation, shipbuilding, welding, hull cleaning, climbing and walking robots.

## INTRODUCTION

The Automatic Control Department of the Industrial Automation Institute (IAI-CSIC) has been carrying out research and development projects in the field of robotic systems for more than twenty five years. Since late seventies this activity began with the realisation of industrial robots, what provided the research team with a wide experience and reputation in robot kinematics, dynamics, mechanical design, and control systems. After some successful developments in that field, the depart-

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ment focused its interest in the area of robots for hostile/hazardous environments. In these kind of environments it is necessary to carry out a variety of tasks (inspection, manipulation, welding, grinding, etc.), what implies human operators are exposed to hard working conditions. Also there are a great number of potential applications that cannot be performed directly by human operators because of difficulties in reaching working positions in a proper and safe way. This situation yields, in a natural way, to the utilisation of remotely controlled devices, where tele-robots can be considered as the most advanced and promising solutions. Doing so a number of advantages will come: improved working conditions, improved safety, automation of repetitive tasks, and opening the possibility of providing innovative solutions to emerging applications.

However, although many applications can be solved by means of an appropriate tele-manipulator, equipped with the right tools and with the concurrence of the human operator skills, many others cannot be solved in this way due to working position difficult access. The problem of accessing to more or less remote job sites presents major difficulties and prevents automation. There are, reported in the literature, interesting solutions to this situation, for example very long reach manipulators. Other, not less interesting approach is to provide a transport mean for the tele-manipulator. Such a transport mean includes wheeled or tracked vehicles, and more recently, legged-machines (climbing or walking).

Nowadays shipbuilding industry is being forced to adapt its production to new technical specifications, shorter delivery time and new safety regulations, so that the ships have to be built faster, more economically and under better environmental condition for operators. New robotic systems are improving these features. Especially, robot manipulators are helping to enhance the quality of welding, decrease arc time, and avoid operators be exposed to fume concentration. However, current robotic systems cannot accomplish some industrial applications, especially those related with mobility in complex environments. These scenarios appear in some stages of the ship construction such as are the operations in the dry dock, and also in the ship repairing yards in what respects ship cleaning and inspection. In this chapter some solutions are presented dealing with specially tailored climbing and walking robots for the maritime industries. These robotic systems have been mostly developed in the framework of European funded projects.

In the field of shipbuilding there are three main stages in the ship erection process:

— Block's construction in the workshop.
— Transportation of blocks to the dry dock or to the slip-way using cranes and especial vehicles.
— Connection of consecutive blocks in the dry dock or slip-way.

The first activity consists of the construction and assembly of huge ship blocks. This work is performed in highly automated workshops with a relatively good productivity, which is being increased by current research in this area. After the transportation of the blocks, which is performed in the second stage, the third involves joining two consecutive blocks by welding together all the longitudinal reinforcements and all the vertical bulkheads.

For environmental safety, most ships, especially tankers and bulk carriers are built with a double bottom and double hull so the cargo will not spill out if the hull is breached. This double structure forms cells all over the ship's hull. There are two important welding problems in ship erection: butt-welding in position along the near-flat external hull surface, and butt/fillet welding for joining double hull cells. In the last years IAI-CSIC has been involved in several projects dealing with welding automation in shipbuilding. Three main results are briefly reported in this work: one six-legged and one four-legged climbing robots for butt-welding of ship hull skin, and one robotic system for welding inside the double hull vertical cells (ROWER 2). All robots have been equipped with industrial welding units and special sensors for seam tracking. A fourth climbing robot, this time underwater, intended for sea adherence cleaning and hull inspection will be the subject of the last part of this chapter.

**REST 1 CLIMBING ROBOT**

The REST 1 climbing robot has six reptile-type legs with three degrees of freedom each one, actuated by dc motors through appropriate gearing. The leg kinematics is of *scara* type, with two rotational articulations and a prismatic one that holds at its end the foot. Feet at the end of legs are provided with special grasping devices based on electromagnets, securing the robot to ferromagnetic-material walls with intrinsic safety. Some degree of compliance has been provided to the feet, by means of an extra passive degree of freedom, so that the robot can adapt itself to a certain extent of surface unevenness. The climbing robot carries on board his control system that consists on an industrial PC that serves as a master for a bunch of slave processors that controls in real time the 18-degrees of freedom. One of the main features is the combination of 6 low-cost/high-performance digital control and 6 power electronic cards (one per leg, each one providing control for 3 joints), specifically developed for this project, and that are the responsible of the just mentioned control of each one of the 18 degrees of freedom of the robot.

The main specifications of the REST 1 climbing robot are:

— Leg number: 6
— Degrees of freedom: 18
— Body frame length: 1100 mm
— Body frame width: 600 mm.
— Robot weight: 220 Kg.
— Robot payload: up to 100 Kg.

Different gaits and control algorithms has been implemented and evaluated. A detail on algorithm preparation is presented in next chapter sections.

**The problem of climbing**

The displacement of a climbing robot is the result of a co-ordinate motion of its legs. This motion is defined by some climbing gait that reflects specifications such as speed, direction etc. There are two phases clearly differentiated in the contribution of each leg to the robot motion. During the support phase every leg should be able to exert a certain force over the climbing surface, in order to provide the necessary forces to the body allowing moving it according to a predetermined path. Later on, during the transfer phase, the leg should displace toward its next support point in order to re-establish the sequence of motion. Each phase imposes a set of requirements to the leg operation. So, during the support phase the leg must have a great capability of force generation, while in the transfer phase the main requirement is the return speed.

The speed and force demand are straight related with the task to be carried out by the climbing robot as well as by the robot location on its environment. Once a task has been defined, the path is established and must be followed by the robot in its working space. The gait will define the state transitions for every leg. Nevertheless, the leg trajectory during the support phase is determined by the body trajectory. There are an infinite number of these trajectories that can be used to obtain the desired robot motion. In order to simplify this selection some authors do the assumptions that: (1) the reachable range of each foot is a rectangular prism, and the feet ranges take up symmetric positions and, (2) each trajectory symmetrically passes the centre $C_i$ of the plane that is the horizontal projection of the reachable area [1,2]. These assumptions, which are based only on the leg mobility, work well for a walking machine on a regular terrain but there are not appropriate for a climbing machine.

One of the big distinctions among the walking and climbing robots reside in the influence of the gravity forces into the robot operation. Depending on the climbing direction, It could be generated some violation of the torque availability conditions associated with the robot's motors. For climbing robots a more reasonable approach towards the selection of foot trajectories should be based on a torque and speed optimisation process along the leg trajectory. The trajectory optimisation problem has been studied widely in the robotics literature [3,4]; generally, the initial and final points are known and the problem is to determine the optimum trajectory that joins both points according with some criterion. The problem exposed in this paper is different since the kind of trajectory is known (i.e. a straight line) while it should be decided its location in the work space, that is to determine the initial position of the leg so that the path is carried out with minimum cost. In this paper we use a torque optimisation approach and a minimum leg velocity criterion in order to select the optimum climbing trajectories during the leg support phase. Later on, we review the influence of the torque restriction over the workspace. Finally, we determine the greatest stroke allowed as a function of the climbing direction.

***Leg placement. An optimum approach***

In climbing robot the acceleration force/ support force ratio is very small. For that reason, in this paper a static force approach is used in order to find the best place for the legs during the support phase.

*Defining the objective function*

Consider a climbing robot, which is hanging on the wall. Let $F_i$ the force applied by the *ith* leg in such a way that the robot centre of gravity remains in equilibrium. The static support torque is given by,

$$\hat{o}_i = J_i\,(q_i)^T \cdot F_i \tag{1}$$

Lets ψ (x,y) the cost function considering the energy of a leg in support phase positioned in coordinates x,y in its workspace, then it can be defined as,

$$Ø(x,y) = \hat{o}^T \cdot \hat{o} = F^T \cdot J \cdot J^T \cdot F \tag{2}$$

where $JJ^T$ is given by,

$$JJ^T = \begin{bmatrix} (l_1s_1 + l_2s_{12})^2 + (l_2s_{12})^2 & -(l_1s_1 + l_2s_{12})(l_1c_1 + l_2c_{12}) - l_2^2c_{12}s_{12} & 0 \\ -(l_1s_1 + l_2s_{12})(l_1c_1 + l_2c_{12}) - l_2^2c_{12}s_{12} & (l_1c_1 + l_2c_{12})^2 + (l_2c_{12})^2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

for a SCARA type leg. Thus, the objective function can be stated as,

$$\begin{aligned} \Psi(x,y) = &\left[(l_1s_1)^2 + 2(l_2s_{12})^2 + 2l_1l_2s_1s_{12}\right]F_X^2 + \left[(l_1c_1)^2 + 2(l_2c_{12})^2 + 2l_1l_2c_1c_{12}\right]F_Y^2 - \\ &2\left[l_2^2s_{12}c_{12} + l_1l_2s_{12}c_1 + l_1l_2s_1c_{12} + l_1^2s_1c_1\right]F_XF_Y + F_Z^2 \end{aligned} \tag{4}$$

Finally, using the kinematic equations for a SCARA leg it is obtained,

$$\Psi(x,y) = \left[y^2 + l_2^2s_{12}^2\right]F_X^2 + \left[x^2 + l_2^2c_{12}^2\right]F_Y^2 - 2\cdot\left[x\cdot y + l_2^2s_{12}c_{12}\right]F_XF_Y + F_Z^2 \tag{5}$$

*Vertical climbing motion*

The objective function varies not only with the x,y coordinates of the leg but also with the F force which in turn depends in the climbing gait. This suggests that for every climbing gait an optimum path will exist that minimise the actuator torque for the leg. In order to solving the foot placement problem it should be necessary to establish it certain considerations. Of the forces that provide support and motion to the climbing robot, the higher contribution belongs to the vertical force. A first approach to the foot positioning problem could be to consider only this force so then the objective function is given by,

$$\Psi(x,y)=\left[x^2+l_2^2c_{12}^2\right]F_Y^2 \tag{6}$$

Consider the support phase time $T_a$ and the leg stroke R. The objective function associated with a x(t), y(t) trajectory could be obtained evaluating the equation (6) along the path. Therefore the trajectory objective function is given by,

$$\Psi_{TRAY}(x_c,y_c,T_a)=F_Y^2\cdot\int_0^{T_a}\left(x(t)^2+l_2^2c_{12}(t)^2\right)\,dt \tag{7}$$

where,

$$c_{12}(t)=\frac{x(t)\cdot(l_1-D(t)\cdot l_2)-y(t)\cdot l_2\cdot\sqrt{1-D(t)^2}}{x(t)^2+y(t)^2} \tag{7b}$$

$$D(t)=\frac{x(t)^2+y(t)^2-l_1^2-l_2^2}{-2\cdot l_1\cdot l_2} \tag{7c}$$

*Including the constraints*

Some constraints must be considered in the optimisation process because of the leg structure and the environment in which the robot moves.

Figure 1 show the workspace for the front leg of an hexapod robot during vertical climbing and different constraints for and specific task (welding on a ship hull). For this task, the environment constraints can be defined as,

$$-0.18<\mathrm{x}(t)<0.280 \tag{8}$$

The structural constraints are due to physical limitation of the leg joints. For the REST robot these are: hip joint (± 90º), knee joint (± 130º), link length (250mm).

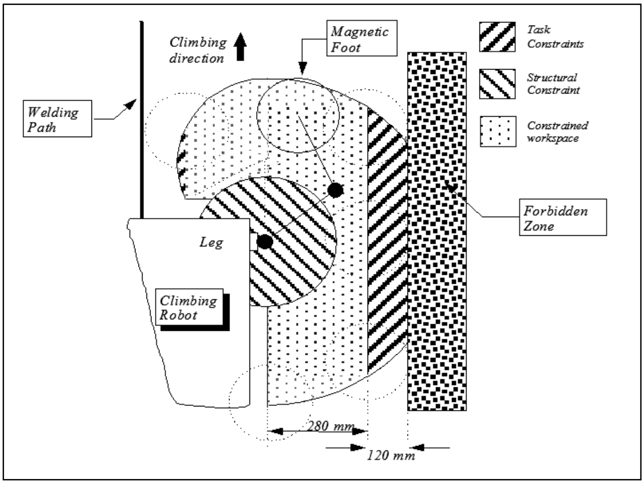



Figure 1 Workspace and structural and task constraints for a hexapod robot

*Getting the location for the optimum leg placement*

Once the constraints are established and the leg path (i.e. a straight line motion) is defined, then the foot placement problem can be formulated as a non linear optimisation problem defined as,

$$\underset{x_c, y_c}{\text{minimize}}\ \Psi(x_c, y_c, R, T_a) = \int_0^{T_a} \left( x(t)^2 + l_2^2 c_{12}(t)^2 \right) dt$$

subject to:

$$\begin{aligned} & x^2 + y^2 < L^2 \\ & -2.27\,\text{rad} < \tan^{-1}\left(\frac{\sqrt{1-D^2}}{D}\right) < 2.27\,\text{rad} \\ & -\frac{\pi}{2} < \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{\sqrt{1-D^2}}{1-D}\right) < \frac{\pi}{2} \\ & -0.18 < x < 0.280 \end{aligned} \tag{9}$$

This is solved numerically using the Optimisation Toolbox of MATLAB [5].

*Numerical results*

In a climbing robot using a periodic continuous gait the robot velocity is

$$V = \frac{R}{\beta \cdot T} \tag{10}$$

so, keeping the ratio $\beta T$ constant ( the robot support forces depend on the duty factor ) its possible to increase the velocity changing the leg stroke. Nevertheless, different legs stroke have different positions of the contact point for the legs that gets minimum actuator torque.

Figure 2 show the constraint workspace and the objective function for a leg stroke of $R$=0.2 mts. and (x,y) trajectory centre.

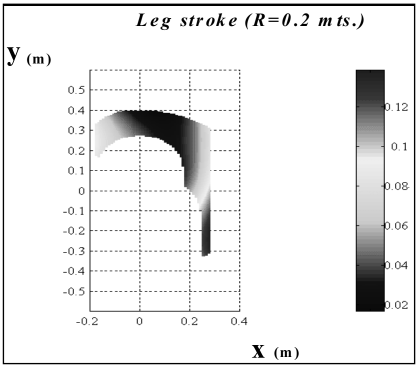



Figure 2 Objective function for a front leg with a stroke of 0.2 m.

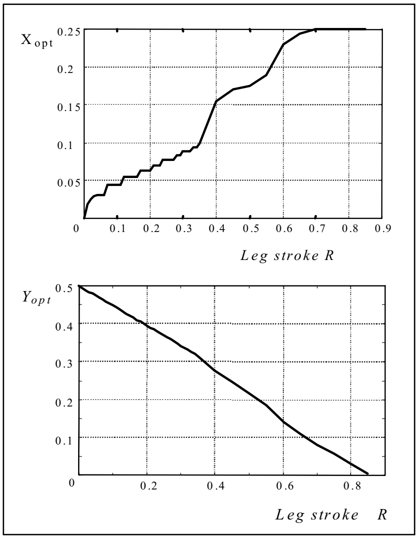



Figure 3 Optimum leg contact position during vertical climbing.

In order to study the dependency of the optimum foot contact position with the leg stroke, it was necessary to run many simulations for different strokes. Figure 3 show the locations of the optimum foot contact position as a function of the leg stroke.

*Omnidirectional climbing.*

In omnidirectional climbing mode the robot can ascend in any direction. This section deal with the foot placement optimisation problem when a climbing robot moves following a straight line and the robot's longitudinal axis set a particular angle $\alpha$ with respect to the vertical climbing.

If two walking robot move following a straight line, over a regular terrain, and use the same gait parameter, changing only the walking directions, they will have the same power requirements. However, this is not true for climbing robots due to gravity force. This suggests that the optimum foot placement depend not only on the leg stroke but also on the climbing angle.

Figure 4 show a climbing robot with an $\alpha$ angle motion direction. Let $F_{Ti}$ be the support force for the *ith* leg and let $F_m$ be the acceleration force so the robot can follow the desired trajectory. The acceleration force can be considered proportional to the support force so $Fmi \approx \kappa F_{Ti}$. Thereby, the *ith* foot force is given by,

$$F_x = F_{Ti} \cdot sen\acute{a}$$
$$F_y = F_{Ti} \cdot cos\acute{a} + F_{mi} \qquad (11)$$

Using eq. 11 and eq.5 the objective function is,

$$\Psi(x,y,\alpha,\kappa) = \left\{ \begin{array}{c} \left[y^2 + l_2^2 s_{12}^2\right] \cdot sen(\alpha)^2 + \left[x^2 + l_2^2 c_{12}^2\right] \cdot \left[cos(\alpha) + \kappa\right]^2 - \\ 2 \cdot \left[x \cdot y + l_2^2 s_{12} c_{12}\right] sen(\alpha) \cdot \left[cos(\alpha) + \kappa\right] \end{array} \right\} \cdot F_{Ti}^2 \qquad (12)$$

For a continuos climbing gait with constant velocity the objective function it is simplified by the condition κ=0.

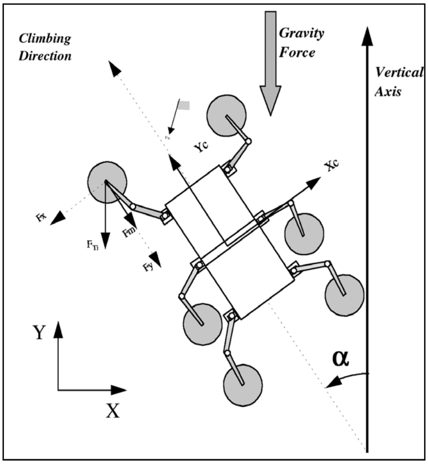



Figure 4
Diagonal climbing robot

Let $T_a$ the support time and R the leg stroke then, the motion cost can be obtained minimising the objective function along the trajectory { $x(t) = X_c$ , $y(t) = Y_c + R/2 - Rt$ } with coordinate value ($X_c$,$Y_c$)) for the trajectory centre. This can be formulated as a non-linear optimisation problem defined as,

$$\underset{x_c,\, y_c}{\text{minimise}}\ \Psi_{Traj}\left(x_c, y_c, \acute{a}, R, T_a\right) = \int_0^{T_a} \Psi\left(x, y, \acute{a}, \kappa=0\right) dt$$

subject to:

$$x^2 + y^2 < L^2$$
$$-2.27\,\text{rad} < \tan^{-1}\left(\frac{\sqrt{1-D^2}}{D}\right) < 2.27\,\text{rad} \qquad (13)$$
$$-\frac{\pi}{2} < \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{\sqrt{1-D^2}}{1-D}\right) < \frac{\pi}{2}$$

*Numerical results*

Some simulations have been carried out in order to find the optimum contact point for different climbing directions. All the solutions are based in a leg stroke *R*=0.25 mts. The robot symmetry permits simplify the problem and solutions for leg pairs (1-6) and (2-5) are the same. Figure 5 shows the optimal coordinates for the trajectory centre for legs 1-2-5-6 as a function of the climbing angle. The discontinuity presented for $\alpha$ = 0.669 rad is related with the structural restrictions.

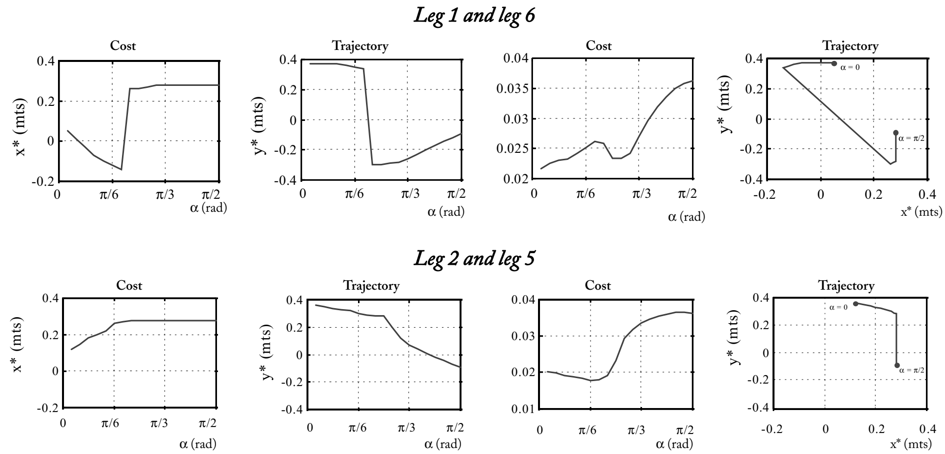



Figure 5 Optimal position for an SCARA type leg of an Hexapod robot

Figure 6 shows the optimal positions for the central legs 3-4 of the hexapod REST.

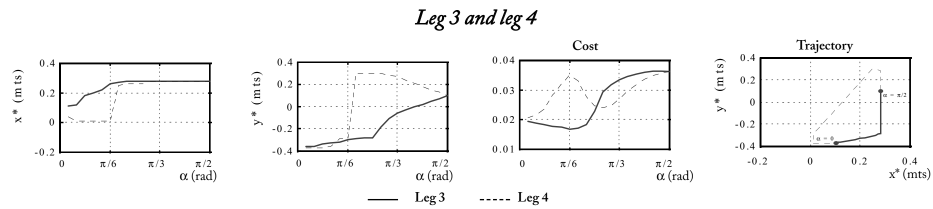



Figure 6 Optimal position for an SCARA type leg of an Hexapod robot. Legs 3-4

Figure 7 shows the climbing sequence for an hexapod robot using optimal foot placement solution for a climbing angle $\alpha = 0.61$ *rad* with a leg stroke $R = 0.25$ *mts*. It can be seen the difference between a climbing robot with optimal contact position and a walking robot using standard leg positioning. In this figure the climbing robot use a Sawing Gait [6] with leg motion sequence {6-3-2-5-4-1}.

Finally, using SIDIREST [7] a comparison between the requirements for a horizontal climbing mode and a vertical climbing mode has been carried out. Figure 8 shows the simulation results for a front leg of the REST hexapod [6] using a wave gait with $\beta$=5/6, $R$=0.3 m and a cycle time $T_c$=12 sec. Figure 8 is an example of duality between the kinematic differential equations (velocity) and static equation (force).

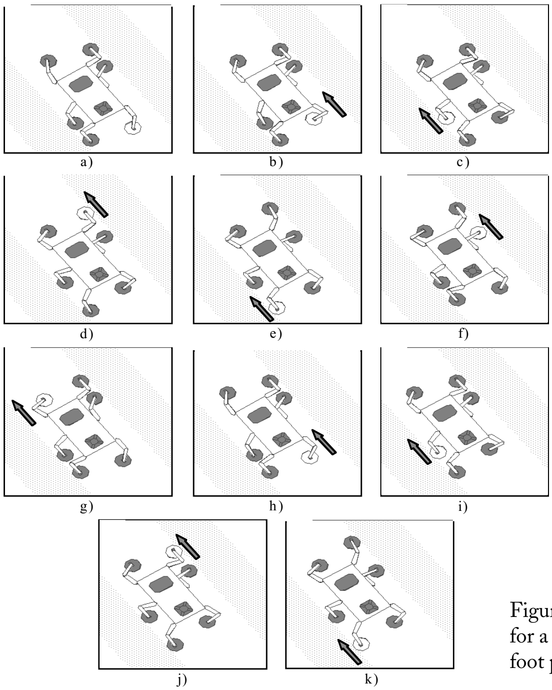



Figure 7 (left) Motion sequence for a climbing robot using optimal foot placement.

TORQUE AND VELOCITY REQUIREMENT FOR HORIZONTAL AND VERTICAL CLIMBING USING OPTIMAL POSITIONS ( LEG 2)

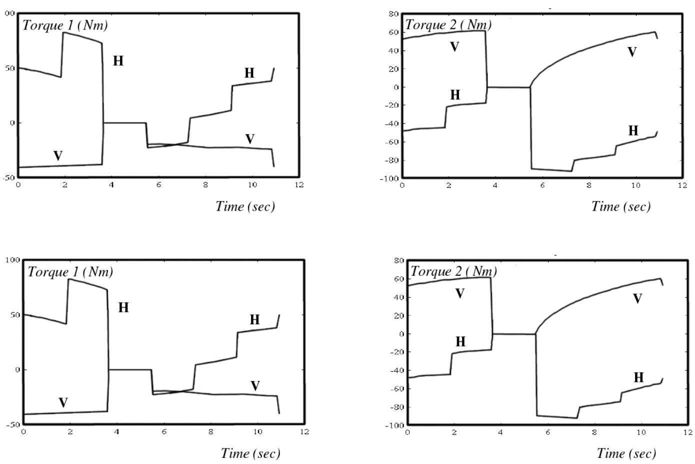



Figure 8 SIDIREST simulation for horizontal and vertical climbing.

Additionally to the torque requirement sometimes is necessary to consider the actuator velocity in order to keep tracked the desired trajectory. The velocity depends on the climbing gait. During the support phase the leg and robot velocity are the same and it is determined for the task while during the leg return phase the leg velocity and the robot velocity follow the relation,

$$V_{leg} = \frac{\beta}{1-\beta} \bullet V_{body} \tag{14}$$

If a duty factor β=11/12 is used, then the leg velocity is 11 times greater than the robot velocity. In this case the velocity must be taking in account in order to satisfy the requirement. The next section deal with the multicriteria optimisation based on torque and velocity requirement.

*Multi-objective Optimisation*

Consider a climbing robot, which is hanging on the wall. Let $\dot{x}_i$ the tip velocity of the *ith* leg during the return phase. The joint velocity are given by,

$$\dot{q}_i = J_i(q_i)^{-1} \cdot \dot{x}_i \tag{15}$$

Lets Γ (x,y) the cost function for a coordinate point (x,y) in the leg's workspace considering the velocity at the foot, then it can be defined as,

$$(x,y) = \dot{q}_i^T \cdot \dot{q}_i = \dot{x}_i^T \cdot \left(J_i(q_i) \cdot J_i(q_i)^T\right)^{-1} \cdot \dot{x}_i \tag{16}$$

where $(JJ^T)^{-1}$ is,

$$\left(JJ^T\right)^{-1} = \frac{1}{l_2^2 \cdot (y \cdot c_{12} - x \cdot s_{12})^2} \cdot \begin{bmatrix} x^2 + (l_2 c_{12})^2 & x \cdot y + l_2^2 c_{12} s_{12} & 0 \\ x \cdot y + l_2^2 c_{12} s_{12} & y^2 + (l_2 s_{12})^2 & 0 \\ 0 & 0 & l_2^2 \cdot (y \cdot c_{12} - x \cdot s_{12})^2 \end{bmatrix} \tag{17}$$

and $\dot{x}_i = [\dot{x}_{xi}\ \dot{x}_{yi}\ \dot{x}_{zi}]^T$.

During the return phase the leg follow the trajectory given by $x_i(t)$ and $\dot{x}_i(t)$ which depend on gait parameter.

*Defining the objective function*

Using a similar procedure of the previous section and considering the eq. 17, the objective function, evaluated on point (x,y) of the return trajectory, can be stated as,

$$\Gamma(x,y)=\frac{\left[y^2+l_2^2 s_{12}^2\right]}{l_2^2\cdot(y\cdot c_{12}-x\cdot s_{12})^2}V_y^2(x,y) \tag{18}$$

An important attribute of this functional is its not dependency with the climbing direction. Considering the return phase time $T_r$, the leg stroke R and a constant velocity $V_r$., then, the objective function could be obtained evaluating the equation (18) along the path. Therefore the trajectory objective function is given by,

$$\Gamma_{TRAY}(x_c, y_c, T_r)=V_y^2\cdot\int_0^{T_r}\frac{\left[y(t)^2+l_2^2 s_{12}(t)^2\right]}{l_2^2\cdot(y(t)\cdot c_{12}(t)-x(t)\cdot s_{12}(t))^2}dt \tag{19}$$

Therefore, considering the objective functions ψ (x,y) and Γ (x,y) the multi-criteria optimisation problem can be defined as,

$$\text{Let}\quad \Omega=[\,\Psi_{TRAY}(x_c, y_c, R, T_a)\ \Gamma_{TRAY}(x_c, y_c, R, T_r)\,]$$

$$\underset{x_c, y_c}{\text{minimize}}\ \Omega(x_c, y_c, R, T_a, T_r)$$

$$\text{subject to:}$$

$$\begin{gathered} x^2+y^2<L^2 \\ -2.27\,\text{rad}<\tan^{-1}\left(\frac{\sqrt{1-D^2}}{D}\right)<2.27\,\text{rad} \\ -\frac{\pi}{2}<\tan^{-1}\left(\frac{y}{x}\right)-\tan^{-1}\left(\frac{\sqrt{1-D^2}}{1-D}\right)<\frac{\pi}{2} \\ -0.18<x<0.280 \end{gathered} \tag{20}$$

There are many methods to resolve a multi-objective optimisation problem. In this paper it is used a weighted sum strategy to convert the multi-criteria optimisation of the Ω vector into a scalar one by means of weight associated with each objective. Thus, the multi-criteria optimisation can be defined as,

$$\begin{aligned} &\underset{x_c, y_c}{minimize}\quad \tilde{\Omega}\ =\ \alpha_1\cdot\Psi_{TRAJ}(x_c, y_c, R, T_a)+\alpha_2\cdot\Gamma_{TRAJ}(x_c, y_c, R, T_r) \\ &subject\ \ to\ \ constraint\ \ Eq\quad 20 \end{aligned} \tag{21}$$

*Numerical results for multi-objective optimisation*

In this section it is considered the same importance for torque and velocity objective. This is established doing $\alpha_1 = \alpha_2 = 0.5$. Those interested readers can see [8] for a general selection of ($\alpha_1$ , $\alpha_2$ ) based on climbing parameters.

The optimisation was carried out for different leg strokes, from 0.01m to 0.8 m. Figure 9 shows the optimum foot contact point for the REST robot during vertical climbing as a function of the leg stroke. It can be see that for a big leg stroke the multi-criteria optimisation converge to the torque optimisation due to restriction in the workspace. For a small leg stroke, R<0.5m, there are fewer motion restrictions. In order to have a general rule to get the foot placement positions an approximated solution was obtained using a fitting least square ninth degree polynomial.

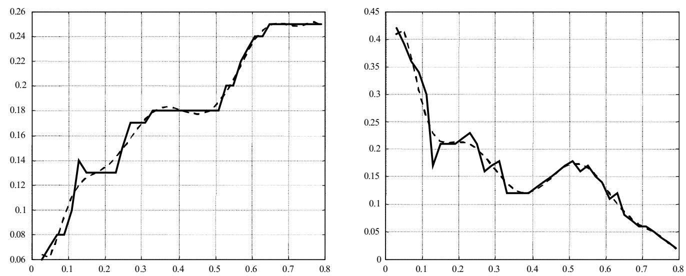



Figure 9 Optimum foot placement for a multi objective optimisation. Vertical climbing

*Influence of the climbing direction on the leg stroke*

Determination of the maximum leg stroke

Let us consider a climbing robot moving on a direction forming an angle $\alpha$. The effective leg workspace varies in accordance with its configuration, with the direction angle and with the support force. In order to estimate the climbing stroke - $R_{max}$ - is required to calculate the maximum stroke- $R^i_{max}$ – that it is associated to robot leg *i*; taking in account that all supporting legs must use the same stroke during the locomotion cycle, then $R_{max}$ is determined by $min\{R^i_{max}\}$.

Due leg configuration affects directly to $R_{max}$, then it is possible to determine the n-legs configuration that permits to obtain the maximum value for $R_{max}$. Let $F_i$ the feet support phase force, and let be $\tau_{imax}$ the maximum torque that can be generated by the *i th* leg actuators. The support trajectory centre is given by the $x_c, y_c$ point. The stroke is *r*. Determination of $R^i_{max}$ can be posed as:

$$
\begin{aligned}
& R^{i}_{max} = \max_{x_a, y_a, r} r \\
& \text{subject to:} \\
& \qquad a)\ x_a^2 + (y_a - \omega \cdot r)^2 < L^2 \\
& \qquad b)\ -\frac{13\pi}{18} < q_{2i}(x_a, y_a - \omega \cdot r) < \frac{13\pi}{18} \\
& \qquad c)\ -\frac{\pi}{2} < q_{1i}(x_a, y_a - \omega \cdot r) < \frac{\pi}{2} \\
& \qquad d)\ J_i(x_a, y_a - \omega \cdot r) \cdot F_i(\alpha) < \tau_{i\,max} \\
& \forall \omega \in [0,1]
\end{aligned}
\qquad (22)
$$

where a), b) and c) are leg kinematic restrictions, while d) represents the associated restriction to the maximum torque allowed through the trajectory. Once determined the values of $R^{i}_{max}$ for each leg it can be determined $R_{max}$ such,

$$
R_{max} = min\left\{R^{i}_{max}\right\} \qquad i = 1,2,\ldots,n \qquad (23)
$$

*Optimisation results*

| Leg | Configuration A | | | Configuration B | | | Stroke Max. |
|---|---|---|---|---|---|---|---|
| | $P_X$(cm) | $P_Y$(cm) | R(cm) | $P_X$(cm) | $P_Y$(cm) | R(cm) | |
| 1 | 3.47<br>-24.35 | 26.75<br>-35.75 | 20.2<br>14.62 | -24.58 | 12.13 | 16.97 | 14.62-16.97<br>20.20 |
| 3 | -2.5<br>-24.35 | 25<br>-35.75 | 16.24<br>14.62 | -24.58 | 12.13 | 16.97 | 14.62-16.24<br>16.97 |
| 5 | -2.5<br>-24.35 | 25<br>-35.75 | 16.24<br>14.62 | -24.58<br>16.17 | 12.13<br>-12.7 | 16.97<br>14.49 | 14.62-16.24<br>16.97 |
| 2 | 24.58<br>-16.17 | -12.13<br>12.7 | 16.97<br>14.49 | 2.5<br>24.35 | -25<br>35.75 | 16.24<br>14.62 | 14.62-16.24<br>16.97 |
| 4 | 24.58 | -12.13 | 16.97 | 2.5<br>24.35 | -25<br>35.75 | 16.24<br>14.62 | 14.62-16.24<br>16.97 |
| 6 | 24.58 | -12.13 | 16.97 | -3.47<br>24.35 | -26.75<br>35.75 | 20.2<br>14.62 | 14.62-16.97<br>20.20 |

Table 1 Maximum leg stroke depending on the leg disposition.

Two different leg configurations have been study. The configuration A represents an "elbow down" leg configuration referred to the first quadrant while configuration B exhibits an "elbow up" disposition referred to the same quadrant. Table 1 presents the obtained results for each leg in the REST robot.

Previous results exhibit how the maximum leg stroke, to be employed during the climbing motion with angle $\alpha=\pi/3$, is $R_{max}$=16cm. This distance can be reached with any of the possible leg configurations, as it is shown in the Table 1.

*Rmax variation with the climbing angle*

Figure 10 represented the variation of maximum leg stroke depending with the climbing angle. It can be seen a strong discontinuity, close to 30º. Starting from this angle the leg's workspace consist of two separated areas reducing the maximum stroke.

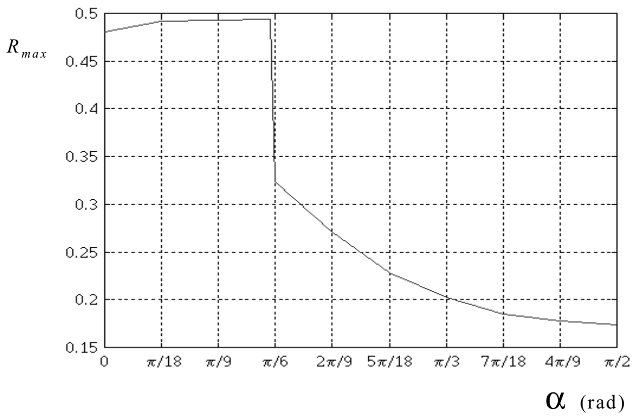



Figure 10 Leg stroke variation with climbing angle

As a summary of this previous sections, the optimum foot placement problem for a climbing robot has been formulated as a non-linear optimisation problem subject to kinematic and environment constraints. The technique permit to select the optimal placement from an energetically point of view. The diagonal climbing has been studied and different foot positions have been established for climbing direction ranging from vertical to horizontal. A multi objective optimisation is proposed in order to consider the velocity requirements during climbing tasks. Finally, the influence of climbing direction in the maximum leg stroke was presented.

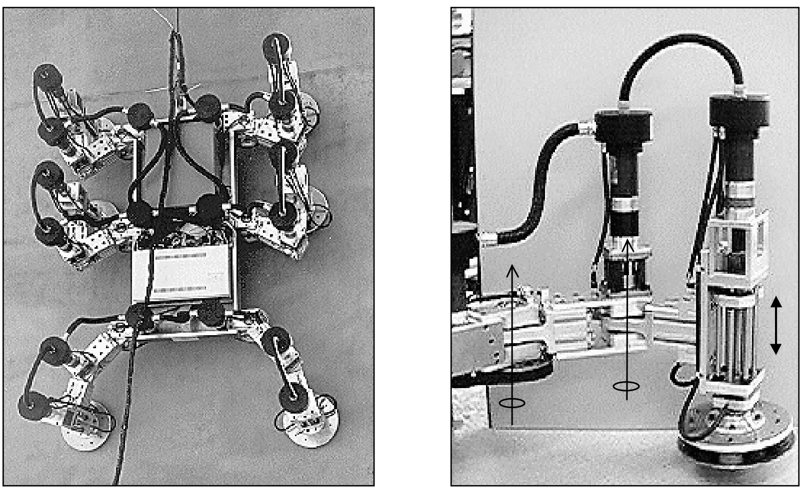


Figure 11 REST 1 climbing robot under experimental testing on a ship hull.

Figure 11 left illustrates the experimental testing of REST 1 six-legged climbing robot on a ship hull, right side shows a detail of the scara type legs.

**REST 2 CLIMBING ROBOT**

Following REST 1, a second prototype of climbing robot that moves continuously along the wall, named REST 2 has been constructed. It uses a variation of the well known wave gait in order to obtain fast continuous movement on softly undulated terrain together with foothold selection to handle obstacles and irregularities during climbing. The robot uses electromagnets to attach itself to ferromagnetic walls and has four legs (12 degrees of freedom) that resemble properties from sliding frames and true legged climbers. The novel leg design and geometrical configuration allows for fully overlapping workspaces. As a result of this novel leg and robot design, it was possible to achieve a much better payload to weight ratio, increased velocity, better inertial properties and reduced energy consumption. Our approach to reliability was to simplify the robot structurally and to support modularity of parts and connections.

REST 2 has been designed to carry on a light manipulator for butt welding. The robot weights less than 50 Kgs. Figures 12 and 13 show a comparison of both climbing machines.

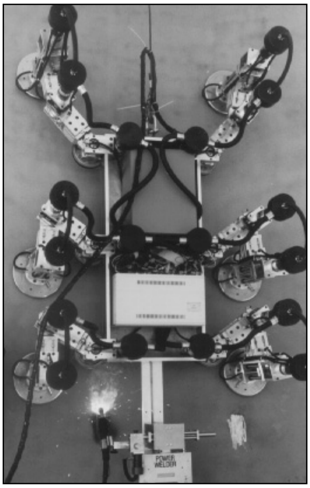
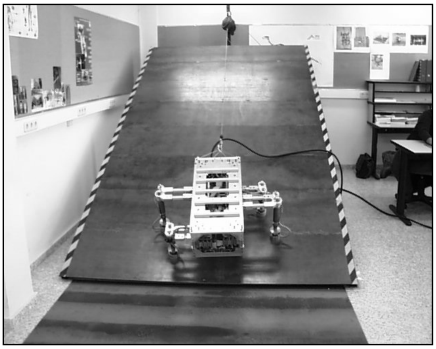


Figure 12. REST 1 climbing robot welding ship hull

Figure 13. REST 2 climbing robot during testing



## ROWER 2

A second development (after ROWER 1) was intended for contributing the problem of welding automation inside the double-bottom vertical cells. So further developments yielded to ROWER 2 (Figure 14), where a light manipulator is moved in the vertical direction for welding the double hull vertical cells.

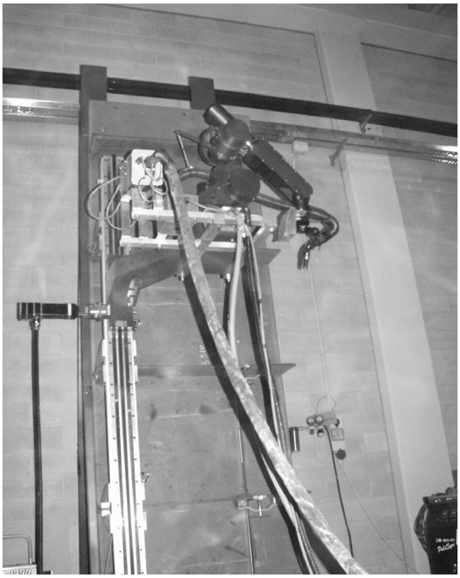


Figure 14. ROWER 2 system.

**AURORA UNDERWATER CLIMBING ROBOT**

It is well known that all kind of ship's underwater hull become overgrown with sea adherence (weed, barnacles) very fast. This means raise of fuel consumption, and freeing atmosphere an extra amount of $CO_2$ (incrementing greenhouse effect) and of sulphur dioxide (acid rain), apart from deterioration of ability of ship's control. This situation becomes important even after six months of ship activity. For recovery of ship's required operational performance, it is necessary for Ship-Repairing and Conversion Industries to dry dock a ship and proceeds to cleaning. This procedure is very time consuming and of high cost, but it is the only available solution nowadays for SRYs. On the other hand, this cleaning activity is the first to be done when a ship needs maintenance and/or some repairing, being the last the main activity of SRYs. So hull treatment is required and, at present time, is done manually in dry-dock using different adapted methods like grit blasting or water jet, and it has to be noticed that, in itself, it is a very contaminant operation (dust contains always painting particles), it is harmful for human operators health and it is a very uncomfortable job.

To provide a solution to these problems an EC funded project (G3RD-CT-000-00246) was organised: AURORA (Auxiliary Climbing Robot for Underwater Ship Hull Cleaning of Sea Adherence and Surveying). The project partnership brings together 7 partners with complementary roles: the Industrial Automation Institute (IAI-CSIC) which is the Project co-ordinator, two ship-repairing yards, T. Kalogeridis&Co. Inc. and Unión Naval de Barcelona, Algosystems S.A., the Division of Robotics, Department of Mechanical Engineering, from Lund University, SAIND, manufacturer and vendor of equipment for shipyards, and Riga Technical University.

AURORA scenario consists in the underwater hull that after some time of ship operation is plenty of marine incrustations, where a new kind of underwater climbing robot equipped with special tools should perform cleaning and surveying tasks. That scenario presents large dimensions and exhibits some areas of very difficult reach-ability and poses some additional technical difficulties. As it has been conceived the underwater climbing robot control is a human-in-the-loop process. Human-Machine Interface (HMI) design takes this into consideration whether using direct control or supervised control. This interface includes a control command set used to select the machine trajectory and a graphic representation used to get information about the robot and its environment. Figure 15 shows the concept of AURORA project and some view of the teleoperation station. Figure 16 shows overall system architecture. The system has demonstrated excellent performance.

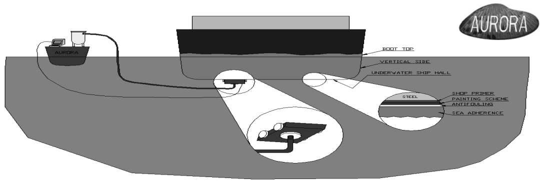



Figure 15. AURORA concept and remote control

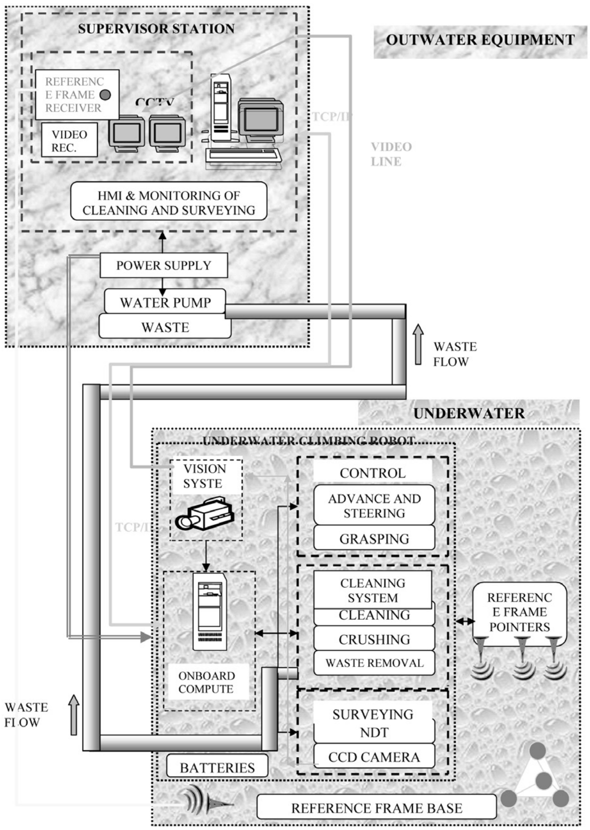



Figure 16. AURORA architecture.

## CONCLUSIONS

Some achievements in the field of climbing robots related to the maritime industries in the last years have been presented. Most of the systems have being conceived to solve practical problems, but a lot of research is underlying and there are still many open questions.

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