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ADAPTIVE CONTROL STRATEGY OF CLIMBING ROBOT FOR INSPECTION APPLICATIONS IN CONSTRUCTION INDUSTRY

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Abstract: This paper presents the implementation of an adaptive control strategy of the climbing robot ROMA2. Its main area of application is an autonomous inspection of complex 3D infrastructure in construction industry, like bridges, skeletons of the buildings, offshore platforms, etc. Due to the fact that gravity factors have a high influence on the quality and security of the motion, the adaptive control strategy has been selected. This strategy is based on the gain scheduling architecture for the most important axis, changing on-the-fly the parameters of the controllers. *Copyright © 2002 IFAC*

Keywords: Robotics, kinematics, adaptive control, parameter identification, adjustment

1. INTRODUCTION

The construction sector is one of the oldest industries. The majority of the old civilisations paid special attention to their buildings and civil infrastructures. They had a very high technological level for their historical period. Nowadays the construction industry continues to be one of the biggest economical sectors, contributing with 7-10% to the GDP of the industrialised countries. Nevertheless, nowadays the level of automation in construction is very low in comparison with the exiting technological level. The manual work continues to be the most common technique. This is why the development of advanced automatic systems for this industry is strongly needed.

This paper presents the development of the adaptive control strategy of the climbing robot ROMA2. Its main area of application is the autonomous inspection of complex 3D infrastructure such as bridges, skeletons of the buildings, offshore platforms, etc. Due to the fact that gravity factors have a high influence on the quality and security of the motion, the adaptive control strategy has been selected. This strategy is based on the gain scheduling architecture for the most important axis, changing on-the-fly the parameters of the controllers. The experimental results of the adopted control strategy are presented and analysed.

2. AUTOMATION IN CONSTRUCTION INDUSTRY

The economical data of construction industry are comparable with the manufacturing industry, but with double investments in R&D for manufacturing (ACEA, 1999). It is evident that nowadays the level of automation in construction is very low in comparison with the exiting technological advances. This is why all the actors (researchers, companies and administrations) must do new efforts to increase the automation level of this important sector (Balaguer, 2000).

The research activities in the field of robotics and automation in construction industry are divided according the applications in two big groups: a) civil infrastructure and b) house building. The most typical civil infrastructure applications are the automation of the road & railway construction (Peyret *et al.*, 2000), tunnelling construction (Girmscheid and Moser, 2001) bridge construction, earthwork, etc. In the field of house building construction the main applications are the building skeleton erection & assembly (Gambao and Balaguer, 1997), the concrete compaction, the interior finishing process, the pre-fabrication (Penin *et al.*, 1998), etc. The classification according to applications is complemented with another possible one, which divides the R&D activities according to the developed technology: a) development of new equipment and processes (robot, automatic systems (Lee, 1998), etc.) or b) adaptation of the existing machinery to transform them into robotic system.

Periodical inspection in construction industry and especially of metallic structures such as those encountered in bridges and buildings' skeletons usually involve a very high number of dangerous manual operations. Most of these are performed in environments that due to their nature imply difficult and dangerous access even for skilled workers. The most relevant examples are inspection of screwed or welded unions of building metallic skeletons and inspection of the painting of the metallic-based bridges (Fig. 1). The possibility of using autonomous robots for these applications presents a very important advantage from the safety and quality point of view (Backes *et al.*, 1997).

Fig. 1. Inspection environment for climbing robot.

The last decade has witnessed an increasing interest in the development of special climbing and walking robots for service applications, specially for building, façade cleaning and inspection. Samples of this include a few well known climbing robots such as those described in (Kamei *et al.*, 1994, Luk, *et al.*, 1995 and Gradetsky, 1998). Nevertheless, these robots are mainly non-autonomous or semi-autonomous in two ways: 1) the control system is wire connected to the “ground” computer where the decisions have been taken, 2) their control systems work in the actuator level only, but not in the locomotion or inspection ones and 3) their control is based on the fix axis controllers.

3. ROMA CLIMBING ROBOTS FAMILY

Since 1995 the University Carlos II of Madrid developed the family of the ROMA autonomous climbing robots for the inspection operations. Fig. 2 shows the first developed robot ROMA1. It is a multifunctional autonomous self-supported climbing robot able to travel into complex metallic-based environment (Balaguer *et al.*, 2000). The navigation is performed by the robot CPU in an autonomous way without other help. The robot is able to self-support its locomotion system for 3D movements, and it has the possibility of autonomous power supply using on-board batteries. In addition to this, it could be umbilically connected to a "ground" power supply to increase the working period for a given task or to allow batteries recharge.

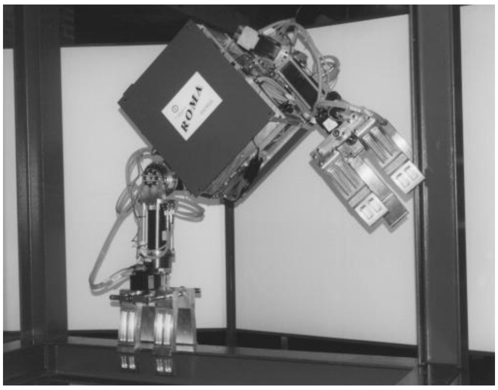


Fig. 2. ROMA1 climbing robot.

The robot has different sensors for inspection operations like cameras (check for rust, painting state, cracks in the structure, etc.), and laser telemeters (localisation of the robot with respect to the metallic structure, and the defects localisation in the structure with the help of the camera). Some of the measured data are used internally by the robot CPU or transmitted to the “ground” centre which is equipped with its own CPU for initialisation, supervision, monitoring and robot programming.

The ROMA1 robot consists of three essential parts: the body of the robot, the locomotion system and the sensorial platform (Fig. 3). The body of the robot includes the CPU, the servo multi-axis controller board (PMAC) which comes with its own low level programming language, one servo motor amplifier (driver), the batteries, the radio-based Ethernet communication with the “ground” operation centre, and other auxiliary electronics.

The locomotion system of 8 DOF formed by two grippers are attached to the robot body and driven by AC brushless servo motors through Harmonic Drive reductors, which permit the 3D movements along complex structures. The 8 DOF kinematics of the robot consist of: a) two elevation and two orientation joints for each of the grippers, b) One rotation joint for gripper 2, c) one prismatic joint for the body “extension” and d) a prismatic joint for each gripper closing and opening movements.

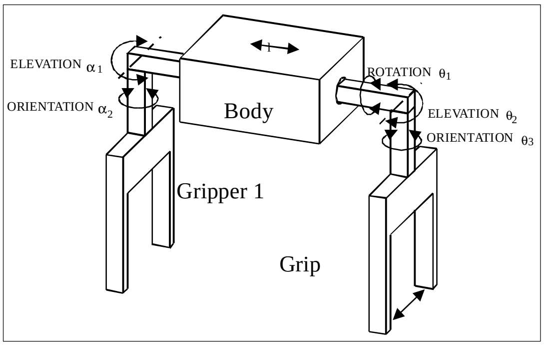


Fig. 3. ROMA1 robot kinematics.

The initial experiments using the ROMA1 robot confirm its advantages and usefulness in executing the inspection operations in complex environments. There are clear indications that this type of robots could replace the human operators in dangerous tasks in the near future. Nevertheless, some difficulties were found during the use of the robot (Gimenez *et al.,* 2001). It is not obvious that this first prototype responds to all requirements necessary for its optimum function such as:

a) Light weight, which is translated to low energy consumption, and consequently increases its autonomy and the payload of the auxiliary equipment.
b) High mobility to allow the robot to move through various environments and on different surface types, geometry and materials (bricks, steel, glass, wood, etc.).
c) The grasping method has to ensure the climbing and displacement in various surface types.
d) High level of autonomy with regard to energy and control.

It has been demonstrated from our experience that it is not possible to incorporate all the above mentioned requirements in the same robot using nowadays technology. A compromise has to be worked out to include the maximum number of the desired specifications.

It is clear that the weight of the robot increases with the number of degrees of freedom. Although a robot with a high number of DOF possesses good mobility, its energy consumption is considerably higher and therefore a good grasp and climbing may not be ensured. The minimum number of DOF necessary to guarantee movement in 3 dimensional complex environments is 6. The ROMA1 robot is built with 8 DOF (6+2 of the grasping tools), which guarantee moving and visiting all faces of columns and beams of a metallic structure, and therefore it is a heavy robot.

The suggested solution for a new version of the ROMA project (ROMA2) is a new prototype with 4 DOF, which is lead to a considerably lower weight of the robot (Fig. 4). The weight of the ROMA robot is decreased from 100 kg. of the first version to less than 20kg. of the second one. The issue of mobility in 3D complex metallic structures is dealt with using more than one robot during the performance of a given task. However, with a few DOF the robot can, also, visit all the faces of the metallic structure. As shown in Fig. 5a ROMA1 robot, with 6 DOF is able to change directly from the face A1 to A2. The ROMA2 is also able to move from A1 to A2, but it is necessary to transit via C1 and B1 faces before (Fig. 5b). Taking into account this fact, it could be possible to optimise the path planning in order to visit all the faces of the 3D structure and decreasing the overall inspection time.

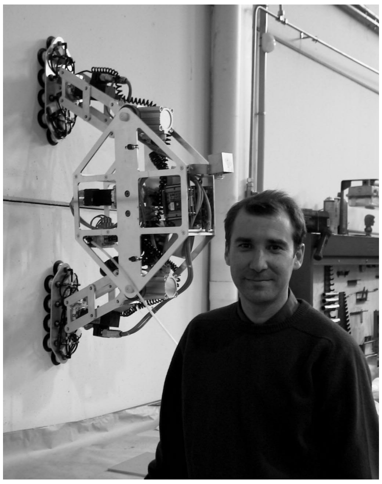


Fig. 4. ROMA2 climbing robot.

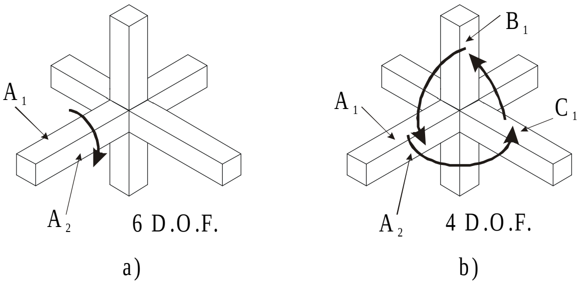


Fig. 5. ROMA1 vs. ROMA2 motion.

4. ADAPTIVE CONTROL STRATEGY

The motion quality, speed and safety are very important for the ROMA robot. The smoothness of the path and safe grasping will be guarantied in all the positions of the robot: in the "floor" (horizontally), in the "wall" (vertically) or in the "ceiling" (upside down). This means that gravity factor strongly influences the robot motion. This is why the adaptive control strategy has been selected. This strategy is based on the gain scheduling architecture for the most important axis, changing on-the-fly the parameters of the controllers.

Three robot axes are driven by brushless AC motors through PID adaptive controllers. These controllers are implemented by a control multiaxis board, which is equipped with its own microprocessor that is dedicated to the robot motion of the control loops only. This leaves the on-board CPU free to process other tasks such us handling the camera image, the laser telemeter, communications, etc.

Each axis controller, in addition to the common PID, includes two feedforward loops (related to velocity and acceleration), with the possibility to change any parameter on-line, even during the motion of the axis.

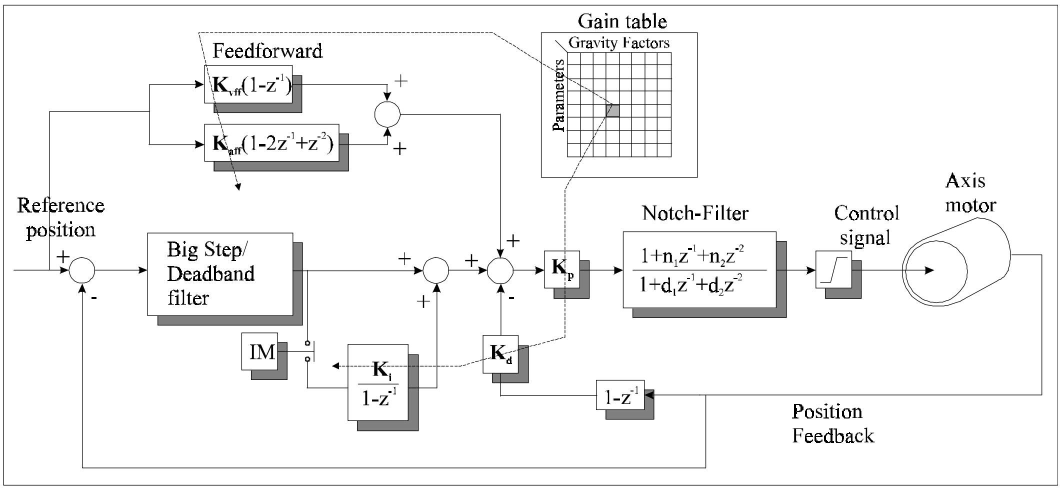


Fig. 6.Adaptive control strategy of the ROMA robot.

Fig. 6 shows the gain scheduling control strategy of the ROMA robot which permits to adjust in-the-fly the parameters of the controllers. Another similar control scheme has been tested successfully in (Gambao, 1996). To find the correct parameters the motor-link system has been identified using the least square method (LSM) with the following equation (Abderahim, 1996):

$$T(t) = I\frac{d^2\theta(t)}{dt^2} + B\frac{d\theta(t)}{dt} + Mglsin(\theta(t))$$
$$+ f_1 sign(\dot{\theta}(t) + |\dot{\theta}(t)|) + f_2 sign(\dot{\theta}(t) - |\dot{\theta}(t)|) \quad (1)$$

where M is the link mass and l is the distance between the axis of rotation and the link centre of gravity in the perpendicular plane to the axis of rotation, T is the torque delivered by the motor, I is the inertia seen at the motor axis (I_{rotor} + I_{load}), B is the viscous friction coefficient, and f_1 and f_2 are the coulomb friction coefficients, and θ(t) is the angular position of the motor at time t. With this equation (1) the gravity loading is not ignored, and is taken into account during the motion control.

Starting from equation (1), the values of the gain tables were calculated experimentally in three stages. First, using the measured values (Fig. 7) and the MATLAB tools, the parameters of the joint model were identified. Second, the identified model was used during the simulation exercise to allow the tuning of the PID parameters. The last part consists of the implementation of the PID controller in the robot and performing a fine tuning to the parameters. In addition, the adequate velocity profiles have been chosen for each joint. The overall objective of this exercise is to achieve smooth movements of the joints in order to avoid rough changes, which may cause vibrations of the mechanical structure of the robot.

In order to collect the data for the identification of the parameters of equation (1) different step signals in both directions are applied to the system. During these motions, the position, velocity and acceleration of the motor axis are collected. All these processes are performed using an open-loop scheme. In this way, the PID implemented later on the control board is not involved in the identification of these parameters. Fig. 7 represents the data obtained with a 2.5V reference input and -1V reference to the axis 2. With these data the identified parameters are shown in Table 1.

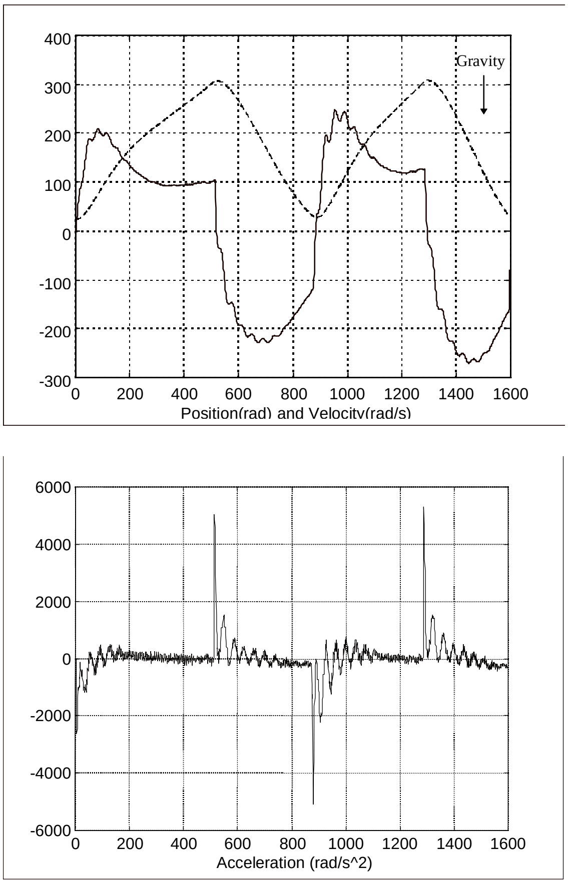


Fig. 7. Position, velocity and acceleration profiles of the axis 2 with gravity factors.

Table 1: Identified parameters of equation (1) for axis 2.

Coefficient	Value
I	1.9533*10^{-4} kgm^2
B	1.4765*10^{-3} Nms/rad
Mgl	2.3903*10^{-1} Nm
f_1	3.5393*10^{-1} Nm
f_2	7.9017*10^{-1} Nm

An example of a gain table can be viewed in table 2 where the associated controller to axis 2 chooses between these values according to the zone of operation. In this case the body of the robot is moved up or down relative to the fixed leg. Therefore, the rest of the motor axes, have various gain tables depending on the nature of the movement. The parameters in the table depend on the direction and the range of the movements.

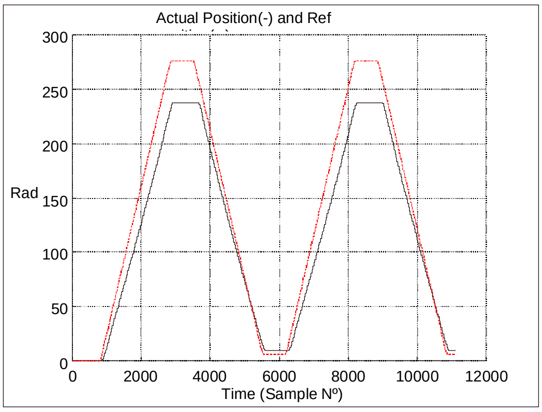
Table 2: Gain table for axis 2.

Range (º)	Dir.	K_p	K_d	K_i	K_{vff}	K_{aff}
-45, 0	⇑	14800	500	400	150	35
0, 45	⇑	14800	400	200	75	35
45, 90	⇑	12500	200	100	50	35
90, 45	⇓	4000	200	100	50	35
45, 0	⇓	4000	180	100	50	35
0, -45	⇓	4000	300	250	50	35

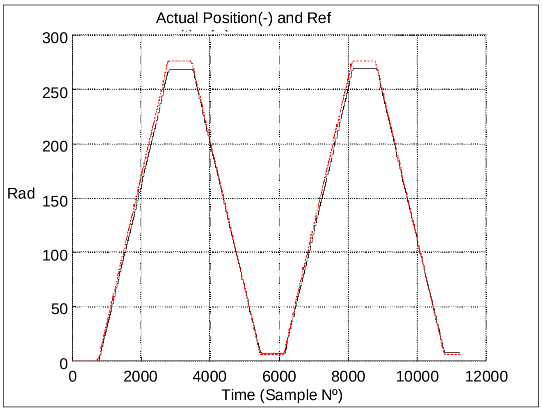
This kind of control is relatively easy to implement in several current computer-controlled systems, being a useful technique for reducing the effects related to the system parameters variation in a simple way. Robots are among the systems, which are indicated for using this type of control, as described in (Åström et al,1995) and (Kelly, 1997).

Figure 8 shows position profiles with different PID's for the control of the motor axis 2. To emphasize the difference between the two graphs (with and without adaptive controller) the results are presented in reference to the motor angle and not the robot axis angle. The top figure illustrates the control position without an adaptive PID, using the values from the second row of Table 2, all the time. The bottom figure illustrates the demanded and the actual position of the same motor when the controller uses all parameters of table 2. In the first case, the tracking of the desired position is acceptable when the joint is moving down and deteriorates when it is moving up. It is clear that the error between the demanded and the actual position of the motor has been improved when the gain scheduling is implemented.

Figure 9 shows the Joint position error at the joint 2, with an adaptive controller. This reflect the actual positioning precision during the manoeuvre. In most of the tests performed, positioning errors at the joint level are very low at the end of the move as shown in figure 9. The move of the figure correspond to a square signal as a reference position



a)



b)

Fig. 8: Actual position and reference position: a) without an adaptive controller and b) with an adaptive controller.

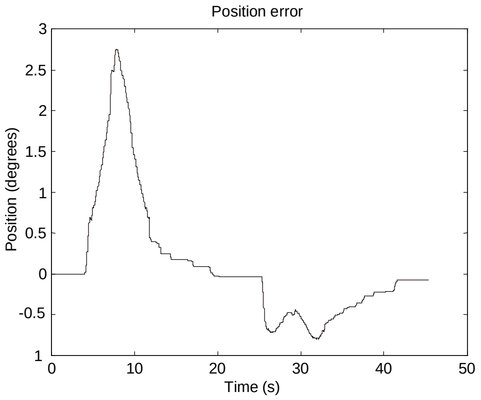


Fig. 9: Position error with an adaptive controller.

5. CONCLUSIONS

The initial experiments have shown that the new version of the ROMA robot is able to climb and to support its weight with sufficient positioning precision. The used powerful on-board sensorial system, is commercially available and easily adaptable for our new application. The improvement of the design of the ROMA robot help to achieve a lower weight and therefore a good grasping force to be used in the climbing.

An existing identification method has been implemented on a real system where the real dynamic characteristics of an existing robot have been identified. The use of this method allows the consideration of all aspects of the model such as gravity and the viscous and coulomb friction. This identification method allows us to obtain the mechanical parameters of the robot in given intervals belonging to the operations zone of each of the motors.

The designed control for the ROMA robot permits using an electric actuator with a reduced overall weight of the robot. This adaptive control achieves a very good precision without ignoring important dynamic aspects such as the gravity. This method is very simple and can be easily handled by the on-board computer. It is necessary to tune the parameters accurately since the ratio climbing force to weight is critical. Actually a variable state control is implemented in ROMA robot, in two ways: using a classical control, or modifying the gains in-the-fly. The preliminary results obtained until now are very successful.

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