Modeling and Control of Multi-Units Robotic System: Boom Crane and Robotic Arm *

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Abstract -

Robotic solutions for the construction industry are attracting the attention of researchers and of the market. Among the various technologies, robotic bricklaying promises to become a disruptive technology. However, most of the solutions proposed so far resulted to be inefficient and did not pass the prototype status. One of the main problems is that most proposed solutions adopt the classic assumption of 'rigid robot' which results in large weight of the robots *w.r.t.* the loads it is able to manipulate. In this paper we propose and analyze an innovative bricklaying concept based on two robotic sub-units: a 'non-rigid' crane which cooperates with a lightweight rigid robot. The correct cooperation between the two robotic sub-units poses a series of control challenges that must be studied in the context of cooperative manipulation of a object. In this paper we will first derive the mathematical model of this robotic system during the positioning of the block. Then a control law will be proposed. The goal of the control is to move the common payload (*i.e.* the block to be placed) to the desired position while making sure the robotic arm is never overloaded. The corresponding stability and convergence analysis is proved using the *LaSalle's invariance principle*. A physical and realistic CAD-based simulator of the overall system has been developed and will be used to demonstrate the feasibility of the concept.

Keywords -

Cooperative control; Robotics; Multi-Robot Systems; Lyapunov methods; Holonomic Constraints.

1 Introduction

With the constant technological advancements, we are assisting to the progressive robotization of many labor-intensive and repetitive human activities. In the current historical phase robots are "leaving" the factories to assist humans in an increasing number of activities. In particular, in the last few years, mostly thanks to the development of new technologies, the use of robotic solutions for the construction industry has grown rapidly [1]. Among the various technologies, robotic bricklaying have in recent years attracted the attention of the public and of the experts and promise to become disruptive technologies. However, very few of the prototypes built in these years have reached the market and can be considered successes.

Most authors [2, 3] agree that the low level of success of robots for bricklaying is due to the fact that developers tried to replicate the solutions developed for the manufacturing industry into the construction context. A major issue is that most solutions are based on rigid arms. In the manufacturing industry robots tend to be much bigger and heavier than the components they manage. This allows the robot to be rigid and to have a very good dexterity in managing the components to be assembled. However since construction materials are often large and heavy themselves, using the same approach results in unreasonably bulky and heavy robots. In [4] a long-range/high payload hydraulic 6-DOF robot for brick assembly named ROCCO was proposed. This machine was able to handle nonstandard and standard blocks with a maximum weight of 350 kg. The prototype of ROCCO weighed 3t and its dimensions were 2.5 x 1.7 m. Given its dimensions and weight, it was nearly impossible to use it on a ceiling slab. Therefore, the prototype was abandoned. Following the same concept of ROCCO, in [5] the robot BRONCO was proposed. Conceptually ROCCO and BRONCO were very similar. However, BRONCO was much smaller but every single pick and place operation was very slow. Like ROCCO, BRONCO did not pass the prototype status and, at the best of our knowledge, this concept was abandoned. Due to the lack of success of robots able to manipulate large and heavy blocks, the market and the scientific publications have turned their attention to robots capable of building with small bricks. SAM100 is the first (and currently the only) commercially available bricklaying robot for on-site masonry construction [6]. SAM100 is based on a standard industrial manipulator with a gripper mounted on a large mobile base. The robot is a very typical industrial rigid robot able to work only with small bricks. DimRob [7] is a prototype mobile construction unit developed in the early 2010s consisting of a standard industrial robot

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arm attached on a mobile base . As SAM100, DimRob was specifically thought to work only with small bricks. Recently the design of DimRob was further refined giving rise to the "In Situ Fabricator" prototype [8]. However, the use of small building bricks has limited use in practice and the global trend (especially for large civil buildings) is to go toward larger and heavier blocks which speed-up the construction process and have better mechanical and insulation characteristics.

In the remainder of this paper we will propose a new concept for the automatic laying of large blocks that we believe has the potential to overcome the main limitations of the designs proposed so far. The solution consists of two robotic sub-units: a 'non-rigid' crane and a rigid robot. This system exploits the characteristics of the crane (and in particular the presence of the lifting cable) to perform the macro-movement of the block and hold most of the weight of the block. The use of the rigid robot allows to obtain the desired precision during the fine placement of the block. The control of the two robotic units poses a number of co-operation challenges that must be studied in the context of cooperative manipulation [9] with the aim of: i) ensuring that the robotic manipulator is able to precisely manipulate large and heavy blocks without being overloaded; ii) carrying out the bricklaying in a fast, reliable, and safe way. From the control viewpoint, the main cooperative challenge concerns the final activity of block placement. In fact, the laying activity of a block can be divided in two main phases. The first phase is the macro-movement performed by the crane. In this phase, the crane lifts the block from the pallet and brings it near its final position. The main difficulty of this first phase concerns the oscillations of the payload which must be counteracted with a proper handling of the crane by the operator. As demonstrated by the authors in [10, 11, 12], for boom cranes this problem could be dramatically mitigated by properly controlling the crane. The second phase is the precision placement, in which once that the robot has grabbed the block, the crane and the robot must be controlled in a cooperative way to carry out the fine-positioning of the block on the wall. In this paper we focus on this second phase. Note that the problem of grasping the swing block has already been addressed in [13], where the authors propose a crane with three wires lifting mechanism to control both the position and the orientation of the block.

Cooperating manipulator systems appear to be a case study of growing interest in the recent literature [14]. This interest is mainly due to typical limitations in applications of single-arm robots. It has been recognized, in fact, that many tasks that are difficult or impossible to execute by a single robot become feasible when two or more manipulators are employed in a cooperative fashion. Such systems are capable of performing a wide range of tasks that include, for instance, carrying heavy or large payloads. Several cooperative control schemes have been proposed in the literature, including motion control [15] and force-impedance/compliance control [16] schemes. Other approaches include adaptive control [17], task-space regulation [18] and joint-space control [19]. To solve the problem of robotic bricklaying, in this paper we address the problem of modeling and control of an heterogeneous robotic system composed of a 'non-rigid' robot, such as a crane, in charge of the macro-movement and of holding most of the weight of the block, and a rigid robot to achieve the desired precision during the fine placement of the block. In the first part of this paper, a mathematical model of the proposed robotic architecture will be derived. On the basis of this model a nonlinear control law will be derived which will allow to control the whole system correctly and safely. A proof of asymptotic stability of the resulting closed-loop system is provided making use of the *LaSalle's invariance principle*. At the end of the paper, a physical and realistic CAD-based simulator of the overall system was developed to demonstrate the feasibility of the concept.

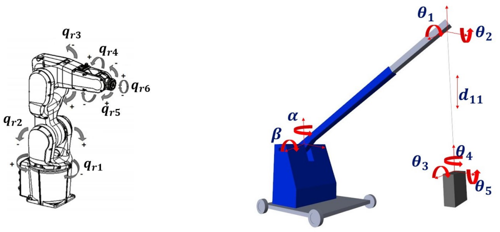
2 Dynamic Model

The proposed robotic solutions is composed by two sub-units: *i)* an industrial robotic manipulator, and *ii)* a boom crane. The manipulator used in this paper is a standard 6-axis industrial robot like the one in Fig.1a. The robot configuration is described by the joint variables vector $q_r \in \mathbb{R}^6$, with $q_r = \left[q_{r1}, q_{r2}, q_{r3}, q_{r4}, q_{r5}, q_{r6}\right]^T$, see Fig.1a. The crane selected for our analysis is a small boom crane (like the one in Fig.1b) which is among the most common types of small cranes used for bricklaying. For the modelling we consider the block to be placed as part of the crane system. For the sake of simplicity, we will also consider the following reasonable assumption.

Assumption 1. All the links and joints of the crane are considered rigid. Moreover, the cable is supposed to be massless, rigid, and always taut, thus the lifting mechanism can be described as a prismatic joint.

Note that this assumption is quite reasonable in most practical applications. In fact the deformations of cranes due to the load are typically negligible w.r.t. overall dimensions of the crane. Furthermore the mass of the payload is usually much bigger than the mass of the cable, which together with the small swing angles that are typically used when operating cranes, makes the assumption on the cable reasonable [20]. The validity of this latter assumption will be verified in Sec.4 where a realistic model of cable based on the Finite Elements Method will be used for the simulations.

The configuration of the crane+block is conveniently described by eight variables, $q_c \in \mathbb{R}^8$, with $q_c = \left[\alpha, \beta, \theta_1, \theta_2, d, \theta_3, \theta_4, \theta_5\right]^T$, Fig. 1b. Where α is the slew angle of the tower, β is the luff angle of the boom, d is the length of the rope, θ_1 is the radial sway due to the motion of the boom, θ_2 is the tangential pendulation due to the motion of the tower, and θ_3, θ_4, θ_5, are the orientations of the block *w.r.t* the cable.



(a) Rigid Arm [21] (b) Boom Crane [22]

Figure 1: Robotic Arm and Boom Crane

The dynamic model of the system can be obtained using the *Euler-Lagrange method* [23] considering as set of generalized coordinates q_r for the robot and q_c for the crane+block. Firstly, for both systems we need to define the *Lagrangian function* as the difference between the kinematic and potential energy. In particular, let the kinematic energy, potential energy, and Lagrangian of the robot be

$$T_r = \frac{1}{2}\dot{q}_r^T B_r(q_r)\dot{q}_r, \quad U_r = U_r(q_r), \quad \mathcal{L}_r = T_r - U_r, \tag{1}$$

while the corresponding quantities for the crane+block system are

$$T_c = \frac{1}{2}\dot{q}_c^T B_c(q_c)\dot{q}_c, \quad U_c = U_c(q_c), \quad \mathcal{L}_c = T_c - U_c, \tag{2}$$

where the matrices $B_r(q_r) \in \mathbb{R}^{6\times 6}$ and $B_c(q_c) \in \mathbb{R}^{8\times 8}$ are the robot inertia matrix and the crane+block inertia matrix, respectively.

The Lagrangian function of the entire system is

$$\mathcal{L}_t = \mathcal{L}_r + \mathcal{L}_c = T_r + T_c - U_r - U_c. \tag{3}$$

To derive the dynamic model of the system we need to introduce a set of closed-chain constraints that come from the interaction between the robot and the crane during the last part of the laying activity where the robot has already grabbed the block that needs to be placed in the final position (see Fig.2). For the sake of simplicity, we assume that the robot grasps the block with a two finger-end effector and that the grip is tight enough so that no sliding nor rotational movements can occur. In this situation, the interaction between the two systems can be model as *holonomic constraints* [24].

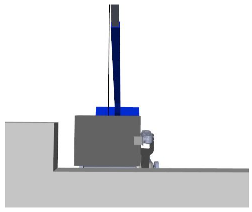


Figure 2: Interaction between the Robot and Crane

To define these constrains, let p_e be the end-effector position, while a minimal representation is used for its orientation, o_e (*e.g.* Euler angles). The robot end-effector pose can be expressed by means a 6-dimension vector

$$x_e = \begin{bmatrix} p_e \\ o_e \end{bmatrix}. \tag{4}$$

Accounting for the dependence of position and orientation from the joint variable, the direct kinematics equation can be written as $x_e = k_r(q_r)$, where $k_r(\cdot)$ is in general a nonlinear function. However, when the robot grabs the block, the robot end-effector pose can also be seen as function of the crane joint variable $x_r = k_c(q_c)$, where $k_c(\cdot)$ is the crane direct kinematics.

This leads to the following *holonomic constraints*:

$$k_r(q_r) = k_c(q_c) \quad \Rightarrow \quad k_r(q_r) - k_c(q_c) = 0. \tag{5}$$

In presence of (5), the constrained model dynamics can be derived using the *augmented Lagrangian*

$$\mathcal{L} = \mathcal{L}_t + \lambda^T \left[k_r(q_r) - k_c(q_c)\right], \tag{6}$$

where $\lambda \in \mathbb{R}^6$ is the Lagrangian multipliers vector that can be interpreted as the generalized forces that arise on the contact interface when attempting to violate the constraints. The equations of the motion of the constrained system are derived using the *Euler-Lagrange equations*

$$\begin{aligned} \frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}}\right)^T - \left(\frac{\partial \mathcal{L}}{\partial q}\right)^T &= \frac{d}{dt}\left(\frac{\partial \mathcal{L}_t}{\partial \dot{q}}\right)^T \\ -\left(\frac{\partial \mathcal{L}_t}{\partial q}\right)^T - \left(\frac{\partial(\lambda^T h(q))}{\partial q}\right)^T &= u + F\dot{q}, \end{aligned} \tag{7}$$

$$\left(\frac{\partial \mathcal{L}}{\partial \lambda}\right)^T = h(q) = 0, \tag{8}$$

where $q = \left[q_r, q_c\right]^T \in \mathbb{R}^{14}$ is the system state vector, $h(q) = k_r(q_r) - k_c(q_c)$ are the constraints expressed by

(5), $F \in \mathbb{R}^{14\times 14}$ represents dynamic friction, and $u = \left[u_{r1}, u_{r2}, u_{r3}, u_{r4}, u_{r5}, u_{r6}, u_{c1}, u_{c2}, 0, 0, u_{c3}, 0, 0, 0\right]^T \in \mathbb{R}^{14}$ is the control input vector. It is worth noting that while the robotic arm is fully actuated (*i.e.* the number of input is equal to the number of DOFs to be controlled, $u_r \in \mathbb{R}^6$), the boom crane is an under-actuated system (*i.e.* $u_c \in \mathbb{R}^3$). In fact, the crane system has only three inputs for 8-DOF as the actuated DOFs are the first two rotations (*i.e.* α and β) and the length of the rope (*i.e.* d).

Substituting (1)-(3), and (6), into (7)-(8), the dynamic model of the constrained mechanical system can be compactly rewritten as the following *descriptor system*

$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} + F\dot{q} + G(q) = u + A(q)^T \lambda \qquad (9)$$

$$\text{s.t.} \qquad A(q)\dot{q} = 0, \qquad (10)$$

where $A(q) = \frac{\partial h(q)}{\partial q}$ is the *Jacobian* of the constraints.

In (9), the matrices $B(q) \in \mathbb{R}^{14\times 14}$, $C(q,\dot{q}) \in \mathbb{R}^{14\times 14}$, and $G(q) \in \mathbb{R}^{14}$ represent the inertia, centripetal-Coriolis, and gravity term, respectively. To simplify the next analysis we introduce the auxiliary variables: $m(q,\dot{q}) = C(q,\dot{q})\dot{q} + F\dot{q} + G(q)$. Matlab® code that contains the dynamic model is released as open-source on GitHub: `https://github.com/MikAmb95/RobotModel`.

The Lagrange multipliers in (9) can be eliminated by differentiating (8) twice *w.r.t* the time

$$\begin{aligned} h(q) = 0 \Rightarrow \dot{h} = \frac{\partial h(q)}{\partial q}\dot{q} = A(q)\dot{q} = 0 \Rightarrow \\ \Rightarrow \ddot{h} = A(q)\ddot{q} + \dot{A}(q)\dot{q} = 0. \qquad (11) \end{aligned}$$

Substituting in (11) the expression of the joint acceleration (*i.e.* $\ddot{q}$) of (9), one obtains

$$A(q)B(q)^{-1}(u + A(q)^t \lambda - m(q,\dot{q})) + \dot{A}(q,\dot{q})\dot{q} = 0. \quad (12)$$

Solving (12) for the multipliers λ, we obtain

$$\begin{aligned} \lambda = (A(q)B(q)^{-1}A(q)^T)^{-1}(A(q)B(q)^{-1}m(q,\dot{q}) \\ -A(q)B(q)^{-1}u - \dot{A}(q,\dot{q})\dot{q}). \quad (13) \end{aligned}$$

Replacing (13) into (9), the constrained dynamic model can be rewritten as

$$\begin{aligned} B(q)\ddot{q} = \left(I - A^T(q)A^{\star T}(q)\right)(u - m(q,\dot{q})) \\ -B(q)A^{\star}(q)\dot{A}(q)\dot{q}, \qquad (14) \end{aligned}$$

where $A^{\star}(q)$ is the inertia-weighted pseudo-inverse of the constraint Jacobian A defined as

$$A^{\star}(q) = B^{-1}(q)A^T(q)(A(q)B^{-1}(q)A^T(q))^{-1}. \quad (15)$$

.

Although the equation of motion (14) is quite complicated, it has several fundamental properties that can be exploited to facilitate the design of the control law. The main property that will be exploited in the next section is:

Property 1.

$$\frac{1}{2}\dot{B}(q) - C(q,\dot{q}),$$

is skew symmetric which means that

$$\eta^T \left[\frac{1}{2}\dot{B}(q) - C(q,\dot{q})\right]\eta = 0, \quad \eta \in \mathbb{R}^{14}.$$

2.1 Control objective

The goal of the control scheme is to ensure: *i*) the correct cooperation between the robot and the crane in order to move the payload to a desired position; *ii*) the safe cooperation between the two sub-units so that the robot will never be overloaded.

To reach these control objective, the first step is to define a desired reference q_d that makes sense. For the problem in hand, in this paper we consider the following properties for the desired reference

Property 2. The desired reference belongs to the workspace of the robot and the crane.

One of the goal of the control scheme will be move the common payload (*i.e.* the block) to a desired position. The constraints (5) imply that once the robot has grasped the block, the desired position and orientation of the block can be seen as a desired pose for the robot end-effector (4). This means that by controlling the six robot joints so that the robot end-effector can follow a desired trajectory, the block can be positioned correctly. Concerning the crane, to limit the forces on the robot, the control scheme must ensure that the crane follows the movement of the payload in the horizontal plane by controlling the two actuated angles (*i.e.* α, β) so that the two oscillations (*i.e.* θ_1,θ_2) are ideally zero. Furthermore, exploiting the cable length (*i.e.* d) the crane control scheme can move the payload along the z-axis (*e.g.* keep the altitude of the block constant, release or lift the block). Concerning the block orientations (*i.e.* the angles $\theta_{3,4,5}$), when the robot has grasped the block *a priori* each robot end-effector orientation could represent a feasible block orientation. However, it is reasonable to think that in the desired position the first two angles (*i.e.* the angles $\theta_{3,4}$) must be equal to zero both for correct alignment with the pre-existing wall and to avoid high torque at the robot wrist due to gravity. Instead the angle θ_5 can be whatever so as to reach the desired block orientation in the final position.

Accordingly to these consideration we will hereafter assume that all desired references are in the form

$$q_d = \left[q_{rd}, \alpha_d, \beta_d, 0, 0, d_d, 0, 0, \theta_{5d}\right]^T . \quad (16)$$

3 Control design and stability analysis

The control strategy proposed in this paper consists of a nonlinear control law based on energy consideration. The corresponding stability and convergence analysis is proved by using the LaSalle's invariance principle.

In order to develop our control law, we start from the following energy function

$$\begin{aligned} E(t) &= \frac{1}{2}\dot{q}^T B(q)\dot{q} \\ &+mg(d - dC_{\theta_1}C_{\theta_2} + l_p - l_p C_{\theta_3}C_{\theta_4}), \end{aligned} \quad (17)$$

where the first term is the kinetic energy of the system, whereas the second term represents the payload potential energy in which m is the mass of the block and g is the gravitational acceleration. In (17) l_p is the distance along the z-axis between the cable-block attachment point and the block Center of Mass (COM), C_i and S_i are the abbreviations for indicating the *sine* and *cosine* function of the angle i.

Based on (17), we can define the following Lyapunov function candidate:

$$\begin{aligned} V(t) \;=\; & \frac{1}{2}\dot{q}^T B(q)\dot{q} \\ & +mg(d - dC_{\theta_1}C_{\theta_2} + l_p - l_p C_{\theta_3}C_{\theta_4}) \\ & +\frac{1}{2}\tilde{q}_r^T K_{pr}\tilde{q}_r \\ & +\frac{1}{2}k_{p\alpha}e_\alpha^2 + \frac{1}{2}k_{p\beta}e_\beta^2 + \frac{1}{2}k_{pd}e_d^2, \end{aligned} \quad (18)$$

where $\tilde{q}_r$ represents the error between the desired and the actual robot posture, K_{pr} is a (6×6) symmetric positive definite matrix. $k_{p\alpha}$, $k_{p\beta}$, and k_{pd} are positive gains, and e_α, e_β, e_d are the crane error between the desired and the current values.

Differentiating the equation (18) *w.r.t* the time and using (14) we obtain

$$\begin{aligned} \dot{V}(t) &= \frac{1}{2}\dot{q}^T \dot{B}(q)\dot{q} - \dot{q}^T B(q)A^\star(q)\dot{A}(q)\dot{q}) \\ &+\dot{q}^T \left(\left(I - A^T(q)A^\star(q)^T\right)(u - m(q,\dot{q})\right) \\ &+mg\dot{d}\left(1 - C_{\theta 1}C_{\theta 2}\right) + \dot{\theta}_1 mgdS_{\theta_1}C_{\theta 2} + \dot{\theta}_2 mgdC_{\theta_1}S_{\theta 2} \\ &+\dot{\theta}_3 mgl_p S_{\theta_3}C_{\theta 4} + \dot{\theta}_4 mgl_p C_{\theta_3}S_{\theta 4} - \dot{q}_r^T K_{pr}\tilde{q}_r \\ &-\dot{\alpha}k_{p\alpha}e_\alpha - \dot{\beta}k_{p\beta}e_\beta - \dot{d}k_{pd}e_d. \end{aligned} \quad (19)$$

Using the Property 1 and considering (10) we obtain

$$\begin{aligned} \dot{V}(t) &= \dot{q_r}^T\left(u_r - G_r(q_r) - K_{pr}\tilde{q_r}\right) \\ &+\dot{\alpha}\left(u_{c1} - k_{p\alpha}e_\alpha\right) + \dot{\beta}\left(u_{c2} - G_\beta(\beta) - k_{p\beta}e_\beta\right) \\ &+\dot{d}\left(u_{c3} + mg - k_{pd}e_d\right) - \dot{q}^T F\dot{q}, \end{aligned} \quad (20)$$

where $G_r(q_r)$ and $G_\beta(\beta)$ are the gravity term of the robot and of the boom crane arm, respectively.

In order to cancel the gravitational terms and keep $\dot{V}(t)$ non-positive, the following controller is designed:

$$u_r = K_{pr}\tilde{q_r} - K_{dr}\dot{q}_r + G_r(q_r), \quad (21)$$

$$u_{c1} = k_{p\alpha}e_\alpha - k_{d\alpha}\dot{\alpha}, \quad (22)$$

$$u_{c2} = k_{p\beta}e_\beta - k_{d\beta}\dot{\beta} + G_\beta(\beta), \quad (23)$$

$$u_{c3} = k_{pd}e_d - k_{dd}\dot{d} - mg, \quad (24)$$

where K_{dr} is an (6×6) symmetric positive definite matrix, $k_{d\alpha}$, $k_{d\beta}$, and k_{dd} are positive control gains.

Substituting (21)-(24) into (20), one obtains

$$\begin{aligned} \dot{V}(t) &= -\dot{q}_r^T K_{dr}\dot{q}_r - k_{d\alpha}\dot{\alpha}^2 \\ &-k_{d\beta}\dot{\beta}^2 - k_{dd}\dot{d}^2 - \dot{q}^T F\dot{q} \le 0. \end{aligned} \quad (25)$$

The following theorem describes the stability property of the system under analysis using the control law (21)-(24).

Theorem 1. Consider the system (14), the controller (21)-(24) makes every equilibrium point (16) asymptotically stable.

Proof: As already seen, the derivative of the Lyapunov function candidate (18) is (25) which is negative semidefinite. At this point let Φ be defined as the set where $\dot{V}(t) = 0$, *i.e.*

$$\Phi = \{q, \dot{q} | \dot{V}(t) = 0\}. \quad (26)$$

Further, let Γ represent the largest invariant set in Φ such that:

$$\begin{aligned} \dot{q} = 0, \dot{\tilde{q}}_r = 0, &\Rightarrow \ddot{q} = 0, \tilde{q}_r = \phi_r, \\ \dot{e}_{\alpha,\beta,d} = 0 &\Rightarrow e_{\alpha,\beta,d} = \phi_{\alpha,\beta,d}, \end{aligned} \quad (27)$$

where $\phi_{r,\alpha,\beta,d}$ are constants to be determined. Combining (27) with (21)-(24) and (9), we obtain

$$\begin{aligned} K_{pr}\tilde{q}_r &= 0, \\ k_{p\alpha}e_\alpha &= 0, \\ k_{p\beta}e_\beta &= 0, \\ gmdC_{\theta_2}S_{\theta_1} &= 0, \\ gmdC_{\theta_1}S_{\theta_2} &= 0 \\ -gmC_{\theta_1}C_{\theta_2} &= -mg + k_{pd}e_d, \\ gml_pC_{\theta_4}C_{\theta_3} &= 0, \\ gml_pC_{\theta_3}S_{\theta_4} &= 0 \end{aligned} \qquad (28)$$

Considering that all the control gains are strictly positive, from the first three equations of (28) we obtain

$$K_{pr}\tilde{q}_r = 0 \Rightarrow \tilde{q}_r = \phi_r = 0 \Rightarrow q_r = q_{rd}, \qquad (29)$$

$$k_{p\alpha}e_\alpha = 0 \Rightarrow e_\alpha = \phi_\alpha = 0 \Rightarrow \alpha = \alpha_d, \qquad (30)$$

$$k_{p\beta}e_\beta = 0 \Rightarrow e_\beta = \phi_\beta = 0 \Rightarrow \beta = \beta_d. \qquad (31)$$

From the other equations of (28), one can be obtained that:

$$\begin{aligned} C_{\theta_2}S_{\theta_1} &= 0, \\ S_{\theta_2}C_{\theta_1} &= 0, \\ C_{\theta_4}S_{\theta_3} &= 0, \\ C_{\theta_3}S_{\theta_4} &= 0. \end{aligned} \qquad (32)$$

The following conclusion can be achieved:

$$\theta_1 = \theta_2 = \theta_3 = \theta_4 = (k\pi) \vee \frac{(2k+1)}{2}\pi, \quad k \in \mathbb{Z}. \qquad (33)$$

However, the only acceptable solution will be:

$$\theta_1 = \theta_2 = \theta_3 = \theta_4 = 0. \qquad (34)$$

By inserting the (34) in the sixth equation of (28), one can conclude that:

$$k_{pd}e_d = 0 \Rightarrow e_d = 0 \Rightarrow \phi_d = 0 \Rightarrow d = d_d. \qquad (35)$$

Note that none of above equations depends on the angle θ_5. However, the final value of this angle is defined by the final orientation of the robot. Then, choosing q_{rd} so that the robot reaches the desired orientation, we can conclude that due to (29), $\theta_5 = \theta_{5d}$, which concludes the proof.

□

4 Simulation Results

In this section we will demonstrate in simulation the effectiveness of the proposed approach. In particular we will show that this solution allows a relatively small industrial arm to manipulate a large and heavy block. To ensure realistic simulations a detailed CAD simulator (see Fig.3) was developed in Simscape™ making use of sub-units already available in the market. In particular the following devices have been selected:

- Crane: NK 1000 Mini Crane produced by NEEMASKO [22], see Fig.5.
- Robot: the ABB IRB 1200 produced by ABB Robotics Fig.6, [21] was selected. This robot weights approximately 50Kg, and it can carry a payload of up to 7kg.

In addition, a realistic wall model is included in the CAD simulator to analyze the possible impacts between the block to be placed and the existing wall. The block to be placed has dimension $0.6m \times 0.8m \times 0.2m$ with a weight of $120kg$. The mechanical properties of the cable are reported in Tab. 1. The cable is modelled using 10 Finite Elements.

Material	Elastic Modulus	Poisson's Ratio	Mass Density
Galvanized Steel	$2^{11}[N/m^2]$	0.29	$7870[kg/m^3]$

Table 1: Crane cable material characteristics

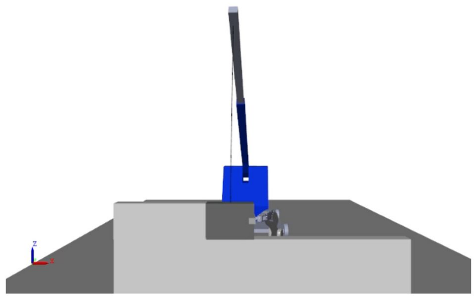


Figure 3: CAD simulator enviroment

The parameters for the control law (21)-(24) are

$$K_{pr} = 1 \cdot 10^3 I_6, \quad k_{p\alpha} = 100, \quad k_{p\beta} = 100, \quad k_{pd} = 1 \cdot 10^4,$$
$$K_{dr} = 3 \cdot 10^2 I_6, \quad k_{d\alpha} = 50, \quad k_{d\beta} = 50, \quad k_{dd} = 7 \cdot 10e^2.$$

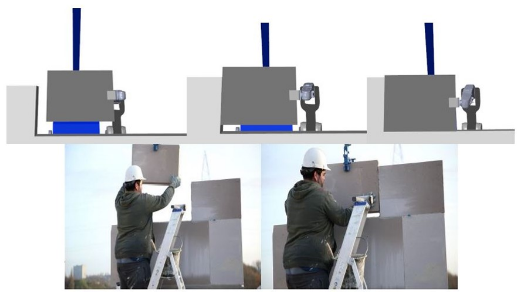


Figure 4: Sequence block placement

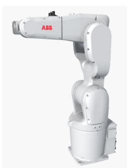
The simulation results are reported in Figs.7-8. The desired references are designed in such a way that the block is moved to its final position. Snapshots of the placement are shown in Fig.4. As expected, Fig.7 shows that the robot joints reach the desired values. Fig.8 shows that the crane actuated states reach the desired configuration. It is important to notice that for the block orientations, the first two angles (*i.e.* θ_3 and θ_4) remain almost equal to zero since the robot is able to damp this oscillations, while the third angles θ_5 rotates according to the robot end-effector trajectory. In Fig.9 the torques applied by the robot motors at each joint during the operation are reported. Most notably, these torques are well within the typical limits of the joint actuators. This means that the mass of the block is sustained almost entirely by the crane and the robot is never overloaded. However it is important to notice that in Fig.9, when the block touches the wall (at around 20 second), there are sudden changes in the torques. Even if their values are reasonable, this suggests that a mechanism for the manage of the impacts should be foreseen. This aspect will be the subject of future studies.

(a) CAD Crane

(b) NK1000p

Figure 5: Boom Crane

(a) CAD Robot



(b) ABB IRB1200

Figure 6: Robotic Arm

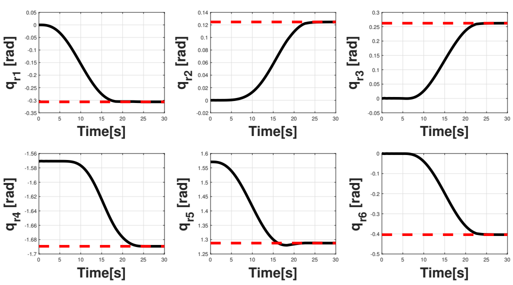


Figure 7: Robot joint positions. Red dotted lines: desired references. Black solid lines: simulation results.

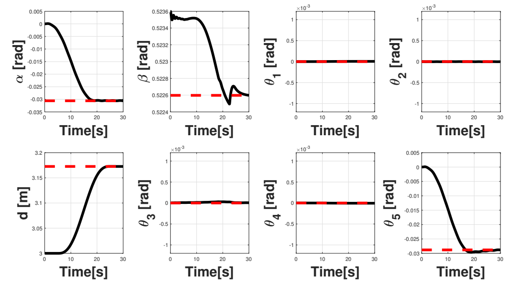


Figure 8: Crane states positions. Red dotted lines: desired references. Black solid lines: simulation results.

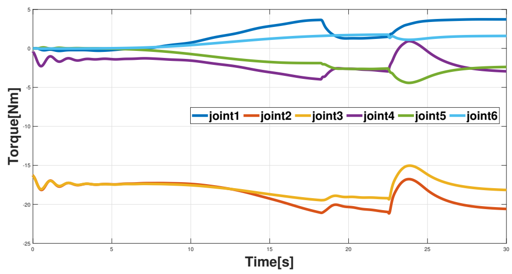


Figure 9: Robot joint torques

5 CONCLUSION

This paper proposes a new concept for the robotic bricklaying of large and heavy blocks based on the crane currently used in the manual bricklaying operations and a rigid robot. This new robotic concept opens to a number of challenges regarding the development of cooperative safety control of this multi-agent system. In the first part of this paper a mathematical model of the overall system is derived. On the basis of this model, a nonlinear control law has been developed which is able to perform position control of the robotic system. The stability properties of the scheme have been proved using the LaSalle's invariance principle. A realistic CAD-based simulator of the overall system was developed to demonstrate the feasibility of the concept. As emerged from the simulations the robot is able to manage quite easily a block that weights the double of its weight.

References

[1] Guglielmo Carra, Alfredo Argiolas, Alessandro Bellissima, Marta Niccolini, and Matteo Ragaglia. Robotics in the construction industry: state of the art and future opportunities. 07 2018. doi:10.22260/ISARC2018/0121.

[2] A. Warszawski and R. Navon. Implementation of robotics in building: Current status and future prospects. *Journal of Construction Engi-*

neering and Management, 124(1):31–41, 1998. doi:10.1061/(ASCE)0733-9364(1998)124:1(31).

[3] Thomas Linner. *Automated and robotic construction: integrated automated construction sites*. PhD thesis, Technische Universität München, 2013.

[4] T. Bock, D. Stricker, J. Fliedner, and T. Huynh. Automatic generation of the controlling-system for a wall construction robot. *Automation in Construction*, 5 (1):15 – 21, 1996. doi:https://doi.org/10.1016/0926-5805(95)00014-3.

[5] G. Pritschow, M. Dalacker, J. Kurz, and J. Zeiher. A mobile robot for on-site construction of masonry. pages 1701–1707 vol.3, 1994. doi:10.1109/IROS.1994.407628.

[6] Sam100. `https://www.construction-robotics.com/sam100/`.

[7] V. Helm, S. Ercan, F. Gramazio, and M. Kohler. Mobile robotic fabrication on construction sites: Dimrob. pages 4335–4341, 2012. doi:10.1109/IROS.2012.6385617.

[8] Kathrin Dörfler, Timothy Sandy, Markus Giftthaler, Fabio Gramazio, Matthias Kohler, and Jonas Buchli. Mobile robotic brickwork. pages 204–217, 2016.

[9] Fabrizio Caccavale and Masaru Uchiyama. Cooperative manipulation. In *Springer handbook of robotics*, pages 989–1006. Springer, 2016.

[10] Michele Ambrosino, Arnaud Dawans, and Emanuele Garone. Constraint control of a boom crane system. pages 499–506, October 2020. doi:10.22260/ISARC2020/0069.

[11] Michele Ambrosino, Marc Berneman, Gianluca Carbone, Rémi Crépin, Arnaud Dawans, and Emanuele Garone. Modeling and control of 5-dof boom crane. pages 514–521, October 2020. doi:10.22260/ISARC2020/0071.

[12] Zemerart Asani, Michele Ambrosino, Andres Cotorruelo, and Emanuele Garone. Nonlinear model predictive control of a 5-dofs boom crane. In *2021 29th Mediterranean Conference on Control and Automation (MED)*, pages 867–871, 2021. doi:10.1109/MED51440.2021.9480259.

[13] H Osumi, T Arai, and H Asama. Development of a crane type robot with three wires. In *Proceedings of the international symposium on industrial robots*, volume 23, pages 561–561. International Federation of Robotics, 1992.

[14] Davide Ortenzi, Rajkumar Muthusamy, Alessandro Freddi, Andrea Monteriù, and Ville Kyrki. Dual-arm cooperative manipulation under joint limit constraints. *Robotics and Autonomous Systems*, 99:110–120, 2018.

[15] Tianliang Liu, Yan Lei, Liang Han, Wenfu Xu, and Huaiwu Zou. Coordinated resolved motion control of dual-arm manipulators with closed chain. *International Journal of Advanced Robotic Systems*, 13 (3):80, 2016.

[16] Lei Yan, Zonggao Mu, Wenfu Xu, and Bingsong Yang. Coordinated compliance control of dual-arm robot for payload manipulation: Master-slave and shared force control. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 2697–2702. IEEE, 2016.

[17] Ying-Hong Jia, Quan Hu, and Shi-Jie Xu. Dynamics and adaptive control of a dual-arm space robot with closed-loop constraints and uncertain inertial parameters. *Acta Mechanica Sinica*, 30(1):112–124, 2014.

[18] Fabrizio Caccavale, Pasquale Chiacchio, and Stefano Chiaverini. Task-space regulation of cooperative manipulators. *Automatica*, 36(6):879–887, 2000.

[19] Christian Smith, Yiannis Karayiannidis, Lazaros Nalpantidis, Xavi Gratal, Peng Qi, Dimos V Dimarogonas, and Danica Kragic. Dual arm manipulation—a survey. *Robotics and Autonomous systems*, 60(10):1340–1353, 2012.

[20] F. Rauscher and O. Sawodny. Modeling and control of tower cranes with elastic structure. *IEEE Transactions on Control Systems Technology*, 29(1):64–79, 2021. doi:10.1109/TCST.2019.2961639.

[21] Abb irb 1200. `https://new.abb.com/products/robotics/industrial-robots/irb-1200`.

[22] NEBOMAT. *NK 1000 User Manual*. NEBOMAT, 2005.

[23] Bruno Siciliano, Lorenzo Sciavicco, Luigi Villani, and Giuseppe Oriolo. *Robotics: modelling, planning and control*. Springer Science & Business Media, 2010.

[24] Alessandro De Luca and Costanzo Manes. Modeling of robots in contact with a dynamic environment. *IEEE Transactions on Robotics and Automation*, 10 (4):542–548, 1994.