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DEVELOPMENT OF AN AUTOMATIC FOUR-COLOR SPRAYING DEVICE CARRIED BY A ROBOT ARM

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ABSTRACT

Automation of building processes is the right mean to improve the average productivity of the construction industry, moreover in case of big and very complex projects. In addition the manufacturing of uniform high quality products can be pursued. This paper is concerned on an automatic system for interior wall painting, which is devoted not only to set an automatic spraying device on one six degree of freedom robot called "Pollock #1", but also to reproduce high quality artworks, using the same principles of four-color cartridges for printing machines. That end-tool was shown to be able to reproduce every color required by designers and, as a consequence, also drawings containing different chromatic scales, through controlling the movement of the arm with respect to the changeable colour mix sprayed by the end tool. Finally, an accurate and efficient automated methodology to reproduce colored drawings from their graphic digital format to their final application on building walls is presented.

KEY WORDS

Multicolor Painting Robot, Construction Robot, Miniature Laboratory, Scaled-Down Laboratory.

1. INTRODUCTION

In this paper a 1:4 scaled down robotized painting end-tool for robots is developed, in such a way that it has the same capabilities of presently marketed colour printing machines, while being able to work in job sites. As it is thought for the industry of construction, its features must be considerably different from the ones used for painting in the automotive industry, or for furniture painting.

There are a lot of factors that can justify the adoption of robots in the construction industry; they are generally roughly divided between [1]:

- improve productivity and save human labour;
- allowing higher quality standards of products.

The first item encompasses on one side the purpose of better management of the whole construction process (lowering time and resource usage for higher incomes) and on the other side the possibility to eliminate human exposure to difficult and hazardous environments, improving the quality of work for employees in the construction industry. However this paper is devoted to the second item: thanks to the specific capabilities of automated machines (e.g. high speed, high precision and accuracy) it is possible to realize artworks that could not be otherwise manufactured through the use of human standard skilled workers, at the same or lower prices than traditional wall painting (with the exception of raw materials and of the more complex device for execution). In other words, it is just necessary to buy more than one colour (three or four depending on the drawing to be reproduced) and to be equipped with the device presented in the following, in order to be able to make wall drawings using the same technique presently used by printing machines for paper printing. In fact we are developing a printing machine for wall painting in buildings, but which needs to be appropriately coordinated with automatic technologies for robotics. This original system can be carried by robots throughout work sites, representing an interesting step forward with respect to all the other non-mobile spraying tools for painting used in industrial chains.

After a preliminary introduction on the main problems connected with spray painting, this paper presents our findings about the manufacturing of an original spraying tool, which is able to manage a four-color (in this paper a three-color application has been experimented) air-mixing device; then it has been mounted on a six degree of freedom robot arm and used during a very successful experimental campaign, that ends up with a novel procedure for artworks' colours reproduction from digital graphic information.

2. DESIGN OF THE SPRAYING TOOL

2.1. State of the Art

The first spraying nozzles date back to the second and third decade of the last century, when they were used in the automotive industry. Instead the first example of pneumatic spraying robot was installed in 1964 by ABB Tallfa Company [2], which was just the prototype of a successful series of more recent devices for industrial chains. On the contrary, not many robots are known in the building sector, and none of them is highly autonomous. The robotic system for bridge maintenance in [3] can be classified as a semi-autonomous robot, because it allows the automated execution of all the operations that would be dangerous when executed by human labor hung under the bridge, but it requires supervision by one or more operators from a safe place on the bridge. Automation is concerned with the robot's capability to make inspection of the bridge, washing, old painting removal and new painting through the use of sensors. However, in order to make painting robots economically convenient for construction, they must be totally autonomous, which is the target of a number of research projects that are presently going on. This argument is presented in [4], where the multipurpose robot TAMIR was used to show how considerable can be savings in labor. But it is in [5, 6] that TAMIR was used to make further experiments with painting: through full scale experiments it was shown that, according to the break-even point technique, robots are always more profitable than human work when highly autonomous machines are adopted. Given this premise, it is advisable to exploit also another feature of automation: its capability to perform high quality works, that should allow to give back high quality final products otherwise not obtainable with the usage of just human labor. In the particular case of this paper we will analyze the possibility to reproduce drawings on interior walls, in the same way it is made by printing machines on paper sheets.

2.2 The Experimental Approach

The work in this paper was carried out in the same laboratory described in [7]. The final aim is supporting a fast development of this technology through the use of a 1:4 scaled-down laboratory, which requires less availability of raw materials, electronic costly equipments and human efforts. Particular attention is devoted to the scaling process from full size to the reduced one, for reproducing actual environments of construction sites.

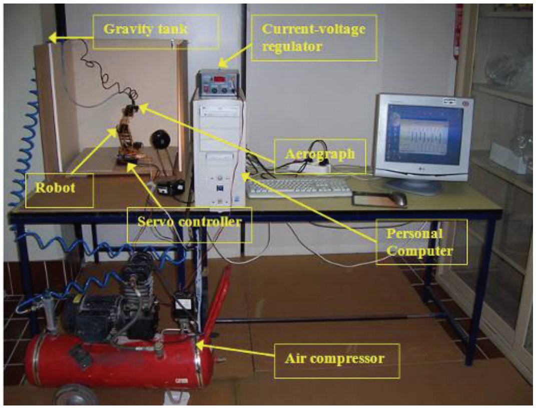


Figure 1 The 1:4 Scaled-Down Laboratory

Figure 1 shows the main components of this small laboratory: one current and voltage regulator (range from 0 to 12 V and from 0 to 6 A); small plaster made surfaces to simulate some building walls mounted on three sides; one 6 degree of freedom robot (Pollock #1) controlled by a 32 channel servo controller connected to the serial port of a PC, having a nominal reach of 0.4 m and a play load of 40 N; one compressor to send high pressure air flow towards the aerograph fed by a tank, which have been modified in the way developed over the next paragraph to allow it to draw multicolor paintings.

2.3 The Painting End-Tool

Every elementary painting equipment is made up of at least the following components: one spray gun, a tank containing paint and a device to lead paint out the tank and send it to the spray gun. There are also three main approaches for painting: Airless; Aerography; Airmix.

The airless painting system works at very high pressure: paint is sent to the spray gun at about $1.2 \cdot 10^6$ Pa (to be created by a pump), whose precise value depends on its physical and state characteristics (density, viscosity, temperature, surface tension, solvent volatility, speed). In this case the jet stream shape is uniquely determined by the nozzle slot, which is generally chosen as vertically oriented. Instead the flow rate of paint is determined by the nozzle extension, which is generally limited from $3.1 \cdot 10^{-8}$ to $1.7 \cdot 10^{-6}$ m^2 [8]. Paint flows through the nozzle at an average speed of about 140 m/s and it is held at about 0.25 m from the wall. Instead aerography produces a jet where air is mixed with paint, which is in turn sucked by air into the gun. It is different from the airless type, that directly atomizes paint through high pressures; in this case paint is sucked by high pressure air (about $4 \cdot 10^4$ Pa) flowing through the spray gun towards the nozzle. Sometimes the gun is fed by gravity or by low pressure, in order to help paint to pass through the gun, but the principle does not change, because in this second case high pressure air is always in charge of paint atomization. This technique is older than the previous one but is not suitable for quick drying paints and produces bigger drops and thicker films, hence lower quality products. In addition, its application is not simple because it generates a paint cloud around the nozzle and it could be dangerous for workers. The airmix system tradeoffs between the two former possibilities, and it is very useful for high precision works. It is practiced through a nozzle that has three holes: one in the centre working in airless mode; other two holes on the sides blowing high pressure air to mold the whole paint jet into the desired shape. Paint is blown between 3 and $6 \cdot 10^5$ Pa, and air is tuned according to the wished final result, whose pressure's magnitude is lower than for aerography (generally between 1 and $3 \cdot 10^4$ Pa).

The possibility to develop a multicolor system for buildings is new: it would revolutionize the concept of building painting and moreover its process. Similar applications are known just in the industrial field: they basically use very heavy paint distributors, which would be difficult to move [9]. Moreover, they mix colors inside the distributors, which is far from the nozzle, requiring long time delays to switch from one color to another. From Fig. 2 it can be inferred that it is important to locate the mixing system as close as possible to the spraying nozzle, in order to quicken the switching.

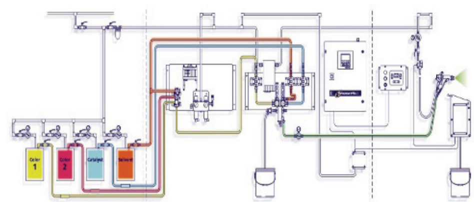


Figure 2 PrecisionMix™ System Delivered by Graco

2.4 The Carrying Robot-Arm and the Whole Experimental Set up

Considering the necessity to tune the shape of the spraying jet according to the size of walls and also the necessity to make experiments in the small laboratory, it was decided to develop a scaled-down airmix spraying gun, whose full scale reproduction can be straightforward. Fig. 3 shows the functioning of the system to be realized: the four primary colors have been put inside high pressure tanks to be sent to the mixing board, which turns up or down their relative amount, previous to their blending into the mixing device close to the gun. Even if it has been designed for four colors, however all the experiments have been performed with three colors: cyan, magenta and yellow. Before showing the whole experimental set up it is necessary to understand how the mixing board in Fig. 4 works. The four color tanks push paint towards the mixing board at high pressure of $1.5 \cdot 10^5$ Pa, which is equipped with four ball valves. Every valve is connected to a servo (deflecting torque equals to 0.132 *kg·m*) which turns up or down the amount of paints flowing through it, establishing the percentage of primary colors to be mixed in the following device and hence deciding the hue of the final color.

Every servo is driven by the same controller of Pollock #1, such that colors are coordinated with the robot's movements. From the mixing board the primary colors move towards the mixing device in Fig. 5-a, which is a hollow aluminum parallelepiped containing one transversal positioned steel spiral, helping the colors to be mixed into the final one. This device is very close to the spraying gun (Fig. 5-b), that is the place where paint is mixed with air flowing at $3.5 \cdot 10^5$ Pa and then atomized while being sprayed. In Fig. 6 we can see all the experimental equipment, mounted in the scaled-down laboratory.

3. PRELIMINARY EXPERIMENTAL CAMPAIGN

First experiments have been made to verify that 1:4 scaling of the distance between the gun and the wall gives back good results when the moving speed is between 0.8 and 1.5 m/s. Then other trials have been devoted to the determination of the following parameters: optimum paint flow rate through the nozzle; optimum paint flow rate through the ball valves of the controlling board. As far as the flow rate through the nozzle, five controlled experiments have been executed, and finally its average optimum value has been computed to be equal to $3.4 \cdot 10^{-7}$ m^3/s. For the sake of understanding the behavior of the ball valve, its characteristic curve describing the paint flow rate with respect to its rotation around its axis from the closed position has been drawn. The valve has been turned on through steps of 15 degrees, and the corresponding flow rate has been measured as pictured in Fig. 7. The relation coming out from Fig. 7 is of basic importance: thanks to that, the controller will be able to compute the required opening of each valve to obtain some pre-established final color starting from the primary ones. It knows that at every step the relative flow rates must be linked by the relation:

$$1 = \frac{Q_C}{Q} + \frac{Q_M}{Q} + \frac{Q_Y}{Q} \tag{1}$$

Where Q is the total paint flow rate, while Q_C, Q_M and Q_Y are the flow rates assigned to each primary color. From the theory of color explained in the next paragraph it is possible to compute every relative flow rate and then the relation in Fig. 7 can be used to compute the required opening for each valve.

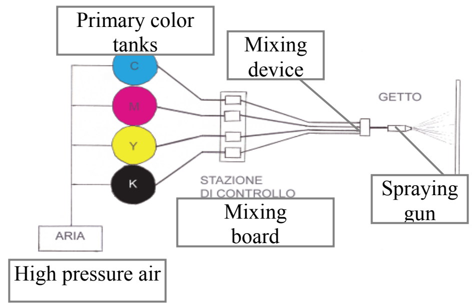


Figure 3 Sketch of the Final Multicolor Airmix Device

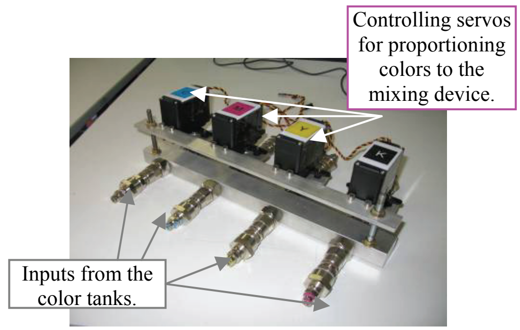


Figure 4 Mixing Board

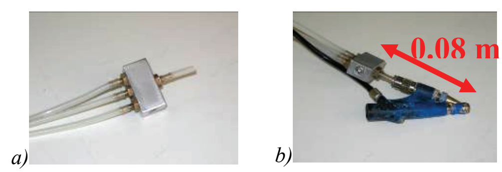


Figure 5 Mixing Device (a) and Spraying Gun (b)

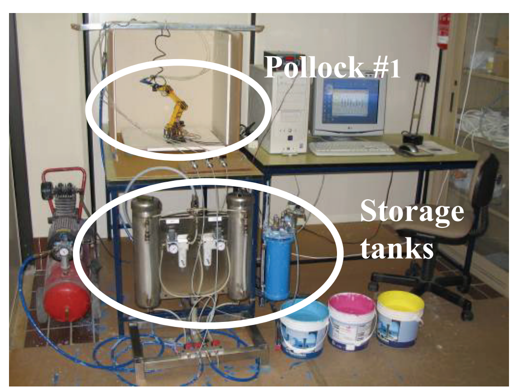


Figure 6 Whole Experimental Equipment

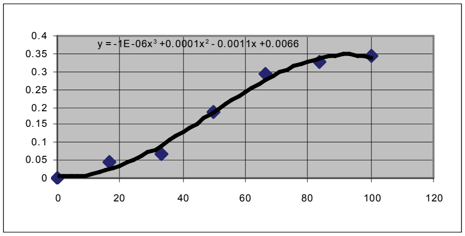
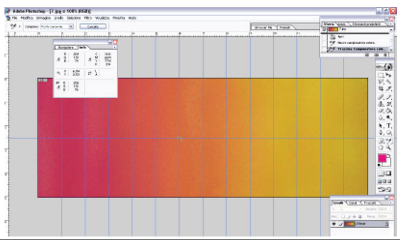


Figure 7 Characteristic Curve of the Ball Valves

Finally, other two trials have been made: analysis of precision and time delay connected to color switching.



Mean	86	84	83	79	71	68	63	58	54	47	41	36	35
Stand. Dev.	2.5	3	2	2.9	4.4	3.3	4.4	4.1	6	7.5	5.3	5.1	7.3
% Stand. Dev.	2.9	3.5	2.4	3.7	6.1	4.9	7	7	11	16	13	14	21

Figure 8 Precision Evaluation

The first analysis have been made by generating a sample of size 9, formed by nine shaded portions of walls of the kind in Fig. 8, from magenta to yellow and other 9 from cyan to magenta. Through a software for imaging processing, the saturation of each sample on a 14 equally spaced column grid has been measured. In Fig. 8 we can appreciate that on each point of the grid, standard deviation measured for magenta on the selected points are low, and on the average equal to 8%. Similar good results have been obtained for the other two primary colors. The time delay has been measure by filming the movements of the servos on the mixing board and the colors sprayed on the walls: the time difference between color switching of the ball valve and the time when it is observed on the wall is the unknown time delay. It has been found out to be equal to 3 s (this time have been considered in the control algorithms used by the controller during painting).

4. A FIRST PROCEDURE FOR REPRODUCTION OF DRAWINGS

One of the most important requirements for such a system is that it can accurately reproduce the colors of every pixel of drawings. For that purpose a general procedure for color reproduction has been set, that is based on the theory of colors [10, 11]. As we are dealing with a system working like printing machines, every color can be thought as composition of the three primary ones: cyan, magenta and yellow (generally also black is included to obtain a wider range in the visible spectrum, however in this experiment it was neglected). We will explain the general procedure while applying it to one real case. First of all a color belonging to the visible spectrum has been generated with the help of a software for image processing (Fig. 9-a), having the following normalized coordinates (C,M,Y) = (0.43,0.06,0.51). Every normalized coordinate is computed from the original CIE (Commission Internationale de l'Eclairage) coordinates (c,m,y) by defining:

$$C = \frac{c}{c + m + y} \qquad (2)$$

and the same holds for magenta and yellow. Then it must be considered that the primary colors used by our system are not the same primary colors considered by the image processing software. Hence three wall samples have been painted using these primary colors and obtaining the following normalized coordinates:

1st primary color (C*) = (0.67, 0.2, 0.13);
2nd primary color (M*) = (0.12, 0.80, 0.08); (3)
3rd primary color (Y*) = (0.05, 0.00, 0.95).

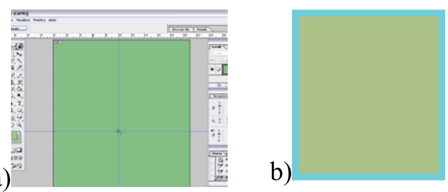
The relative amount of the system's primary colors (C^*,M^*,Y^*) to be used for the reproduction of the original color (C, M, Y) have been computed by solving the following system:

$$\begin{cases} C^* + \alpha_c M^* + \beta_c Y^* = C \\ \alpha_M C^* + M^* + \beta_M Y^* = M \\ \alpha_Y C^* + \beta_Y M^* + Y^* = Y \end{cases} \qquad (4)$$

Where the coefficients α and β allow for the non purity of our primary colors. For instance, if we know that the system must spray a certain amount of cyan (C), it is present not only in its cyan (C*) but has also other contributions in its magenta (α_c=12% and β_c=5%), as suggested by eq. (3), from which all the other coefficients have been determined. The unknown variables have thus been determined to be (C*, M*, Y*) = (0.476, 0.025, 0.54). Then applying eq. (1) in the following form:

$$1 = C^* + M^* + Y^* = \frac{Q_C}{Q} + \frac{Q_M}{Q} + \frac{Q_Y}{Q} \quad (5)$$

And by the knowledge of the optimum flow rate Q, it was possible to compute the single flow rate values Q_C, Q_M and Q_Y; from these values and from the diagram in Fig. 7, valves' openings were determined and the final color was sprayed on a plaster wall sample (Fig. 9-b). Observing the two figures it is possible to appreciate that they are very similar.



a) b)

Figure 9 Original Color (a) and its Reproduction Through our System (b)

But this check has been performed also using a scanner acquisition system: it gave back the normalized values (0.53, 0.58, 0.31) for Fig. 9-b, which have been corrected by the knowledge of the shift introduced by that scanner (previously determined scanning pure primary colors from [11]), that is (+0.20, +0.06, -0.26). Hence the corrected value of the color sprayed by our system was (0.33, 0.1, 0.57), whose difference with the original one is (-0.1,+0.04, +0.06), that is the approximation introduced by the whole mechanical system.

5. CONCLUSIONS AND FUTURE RESEARCH

Thanks to the mixing equipment developed throughout the research step described in this paper, we have shown that automated painting can be not only aimed at improving productivity, but also quality. The next step will require re-scaling back of these results to full scale and further studies for development of control algorithms that could allow reproduction of more complex graphic patterns. Those experiments will be useful also to discern the limit of accuracy that can be pursued by such a system, depending on the variation of some parameters like time delays connected to switching.

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