SET UP OF A ROBOTIZED SYSTEM FOR INTERIOR WALL PAINTING

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Abstract: Although the use of spraying robotized systems for interior painting was already shown to be feasible and convenient, a lot of experiments must be carried out in the future to deliver a highly autonomous robot for interior painting. A new approach is proposed: two laboratories are set, the former being a full-scale and the latter a 1:4 scaled-down one, which is equipped with one robotized spraying machine (called "Pollock #1"). Thanks to its reduced size, less amount of raw materials, power supply, maintenance effort and wall surfaces for testing are required and experimental tests go quickly. This paper describes the experimental set-up constituting the scaled laboratory and analyzes proper trajectories for the robot's spraying end-tool. In addition, the problem of re-scaling back the obtained results to full size buildings is addressed. Finally, the first experimental results obtained in the foregoing scaled laboratory are discussed, showing the very good performances of Pollock #1.

Keywords: painting robot, highly autonomous robot, Pollock #1, scaled laboratory.

1. INTRODUCTION

As shown by some feasibility analyses relative to the automation of interior finishing construction processes, there are both economic and qualitative factors that could justify the adoption of robotized systems. Savings in human labor and in timing are only the two main advantages; besides them we must consider the opportunity to reduce or eliminate human exposure to difficult and hazardous environments, and to improve the quality of such works. Valuable experiments were led in ref. [1] to verify how convenient is carrying on interior-finishing works through robots. In particular, painting was executed using a spray gun with its on/off control nozzle operated by connections of the multipurpose TAMIR robot's controller. Results of comparisons at full scale between labor and robotized execution showed that there are significant savings in labor, depending on the labor rate, when auxiliary work is considerably lessened. The same robot TAMIR was used for other experiments more deeply concerned with painting in ref. [2, 3], where the degree of human and robot integration is studied, in order to develop very efficient robots, through the description of the break-even point that makes automation more convenient than labor. Through the performance of full scale experiments, it was possible to show that robots are always more profitable than human work when highly autonomous robots are adopted, because one operator may supervise also two different robots; in this way it is convenient also for cheap labor markets. This is due to the fact that human workers are released to the simultaneous performance of complementary subtasks, which might improve the profitability of the system.

The feasibility of highly autonomous robots is shown by a number of papers, thanks to the adoption of navigation systems that can be implemented inside controllers, in order to reduce auxiliary work from labor. In ref. [4] a prototype of highly autonomous plastering robot was tested in a full scale construction site: it is able to measure the size of the environment and to execute its operations autonomously, under the control of an operator, using range measuring sensors scanning in one or two planes. Even if good results were obtained inside a room, further sensors would be needed to perform the same operations in an apartment or in whole buildings. The time used for plastering the walls and ceiling in a room is expected to be less than 50% of that required by manual work and the amount of plaster used is greatly reduced. More accurate and advanced navigation systems were sown in ref. [5] and [6]: the former is relative to preliminary application of the range-weighted Hough transform, while the latter is relative to an algorithm for environmental mapping by integrating scans from a time-of-light laser and odometer readings to produce data from which approximated lines were extracted through the range-weighted Hough transform.

The authors in this paper are proposing an innovative approach for quick development of a robotized system, specifically for interior wall painting, as this is one of the tasks that will be always executed on site, also in the future when building components are expected to be manufactured off-site and then assembled on-site. Considering that from previous research the feasibility of such a system was demonstrated, now it is necessary to develop a highly autonomous robot for wall painting, that must be able to move in the construction site with minimum operator intervention. In addition, the final arrangement of this prototype is thought to be able to perform not only fast and efficient painting, but also high quality pictures, working in a way similar to the one of printing machines. In this way users will be allowed to draw pictures on the interior surfaces of building walls obtaining good aesthetic results even if with low economic investments. In order to support fast development of such a technology, two laboratories are set: one 1:4 scaled-down laboratory to perform preliminary experiments with less use of raw materials and electronic and human efforts; one full size laboratory to verify the actual reliability of the proposed solution when the probability of success is very high, thanks to the scaled tests previously performed. To make this approach feasible it is necessary to meet some requirements:

- scaled-down and full size experiments must be performed in comparable ways;
- scaled-down and full size equipments must be of the same types;
- empirical or analytical models must be worked out at the scaled preliminary testing level, in order to infer the results that would be obtained when working with the corresponding full scale arrangement.

Therefore this paper describes the scaled-down laboratory and an example of development of a model that could be used for re-scaling the results obtained from scaled down experiments to full size. In particular the model is referred to the determination of the paint quality (uniformity and saturation) with dependence to some parameters that affect it. Varying those parameters in the scaled version, it is possible to estimate which results would be obtained in an actual construction site. Finally, that model is validated through comparison with experimental results, showing its good accuracy for this particular case and suggesting likely developments for future research, in order to produce a robotized prototype for interior wall painting.

2. AUTOMATED PAINTING

Presently automation is very spread in the field of industrial engineering, where there are a lot of patented prototypes, like robots for car painting (e.g. in ref. [7]). However construction sites own peculiarities that require highly autonomous systems, able to deal with hazardous and complex environments, where every robot must navigate by itself, and just repeating iteratively the same operations is not satisfactory. A very good intermediate solution was proposed in ref. [8], where a robotic system for bridge maintenance was developed. It owns all the advantages that are typical of automation, like autonomous execution of all the operations that would be dangerous for operators hung under the bridge, who instead are allowed to supervise every step from a safe place. The robot arm is based on a platform to be fixed on the bridge; two cameras on the robot arm allow for bridge inspection and then an algorithm elaborates opportune movements that are necessary for maintenance operations like washing, old painting removal and then new painting. During the work all the parameters affecting painting quality are automatically optimized, according to the requirements of the specific bridge considered. That one is an example of semi-autonomous robotic system, where any transportation or maneuvering is done by the operator (hence orientation and navigation systems are not necessary), while the final work is executed by the robot autonomously. In order to make a painting robot economically convenient for construction sites, it must be equipped with navigation and orientation systems, that would make it totally autonomous and which is the final target for researchers who want to develop painting robot prototypes. The first step to reach that purpose is however manufacturing proper end-tools and stating correct spraying rules, that could restitute high quality works. As a consequence to that, it will be possible to individuate proper requirements relative to robot features.

The main parameters affecting painted wall quality are: type of painting process; trajectories of the end-tool; motion speed; spraying paint flow; type of paint; dilution; air pressure; distance from the wall. Some of them are fixed by regulations and standards, other must be optimized by operators, with reference to the actual work to be executed. Before testing the 1:4 scaled-down robot, all these parameters were optimally set for the full scale case, and then they were properly reduced for preliminary testing. As far as concerns the type of spraying, there are three main types: aerography, airless and mixed. For the purpose of this work the first type was chosen and proper trajectories were chosen testing the quality of painting through the device shown in Fig. 1-a. Fig. 1-b and Fig. 1-c show the chosen paths to be drawn by the end-tool to obtain a uniform good quality coat without any of the defects listed in standard UNI EN ISO 4618/2, where the distance between two lines is limited from 0.15 to 0.25 m and the distance from the wall is between 0.3-0.35 m, with an average value of 0.32 m adopted for our tests. Empirical experiments showed that motion speed may vary from 0.8 to 1.5 m/s; the spraying paint flow vary with nozzle's dimension and was set to 1.2 g/s; dilution of the utilized water-base paint is fixed by the paint's supplier; air pressure is suggested by standard UNI 10997 (for this case it is limited between $2.7 \cdot 10^5$ and $3.5 \cdot 10^5$ Pa).

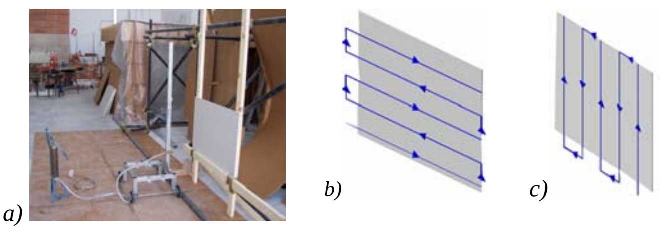


Fig. 1:experimental device for trajectory testing (a) and horizontal (b) and vertical (c) trajectories chosen.

Once that a full scale procedure for high quality painting was set through the device of Fig. 1-a, that was able to manually reproduce the trajectories that would have been drawn by an automated machine, the passage towards reduced scale experiments was performed by scaling all the parameters listed above. The following ones were fixed:

- type of spraying: aerography;
- trajectories: a two coat paint was applied on the internal surface of plaster walls, following the schemes depicted in Figg. 1-b and 1-c;
- type of paint, that is water-base;
- air pressure, set at $3 \cdot 10^5$ Pa;
- distance from the wall, equals to 0.08 m;

− paint flow was set to 0.3 g/s through the adoption of a small aerography spraying on a circle having a 0.06 m long diameter.

Instead the motion speed and distance steps between two lines were allowed to vary:

− speed was scaled to a range limited between 0.036 ad 0.11 m/s;
− step between two lines of trajectories was left to vary from 0.04 to 0.05 m.

Thanks to this transformation of parameters it was possible to perform scaled-down experiments, with the warranty that re-scaling back would give good quality painting. A mathematical model was built, to allow the possibility to properly set each parameter inside the optimal ranges previously individuated before full size experiments.

3. SCALED-DOWN LABORATORY AND TESTS

3.1 Premise

As stated earlier, a 1:4 scaled-down laboratory was set to carry out cheap preliminary experiments and being careful to establish a direct link with full scale tests, in order to be able to re-scale back the results obtained to infer optimal full size painting conditions starting from preliminary outcomes. The main purpose is the one of reproducing actual environments of construction sites with minimum utilization of raw materials, power supply, maintenance effort and wall surfaces to test. In addition, wrong settings of the control system, that could cause damages of building elements in the scaled-down laboratory, would be considerably less expensive – hence less worrying – than damages in the full scale laboratory. Fig. 2 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 reproduce 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 installed on the end tool of the robot and fed by a gravity tank, where paint is stored.

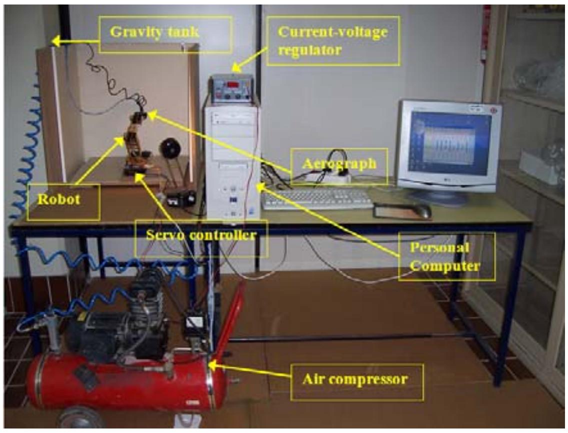


Fig. 2: 1:4 scaled down laboratory.

That robot is made up of a supporting rotate base fixed on a two degree of freedom hexapod for horizontal moves (not exploited for the experiments proposed in this contribution), an arm with three rotary motions whose end is equipped with a rotary wrist and a gripping hand (Fig. 3-a). The whole robot owns 6 servos (one for each degree of freedom excluding the hexapod). For this testing the gripping hand was substituted with the aerograph, that utilized the servo used for gripping to rotate horizontally and is fed by gravity as shown in Fig. 3-b.

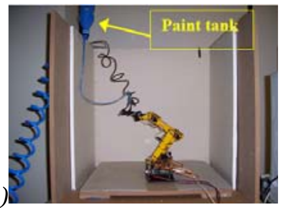
a)  *b)* 

Fig. 3: six degree of freedom robot "Pollock #1"(a); tank containing paint feeding the aerograph by gravity (b).

Every servo is controlled by a small preassembled servo controller with some big features. It has high resolution (1uS) for accurate positioning, and extremely smooth moves. The range is 0.75uS to 2.25uS for an angular range of about 170°. The motion control can be immediate response, speed controlled, timed motion, or a combination. A unique "Group Move" allows any combination of servos to begin and end motion at the same time, even if the servos have to move different distances. Every servo's position or movement can be queried to provide feedback to the host computer.

Thanks to this arrangement it was possible to reproduce the movements that are used to paint walls with aerographs like in Figg. 1-b and 1-c. Similar trajectories were studied also for most complex cases like columns, beams and corners.

3.2 The Model for Rescaling to Full Dimensions

Every time that experimental tests are conducted within the scaled-down laboratory, it is necessary to create a model (of empirical or analytical type) that allow to re-scale back to the full size by simply changing some parameters.

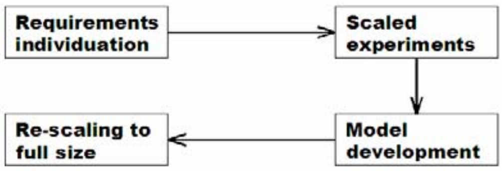


Fig. 4: The role of model development.

Fig. 4 sums up this concept: once that requirements are fixed and they are divided into the categories of fixed and variable types on one side and of dependent and independent types on the other side, the model can be built for the scaled down case; then the first results can be re-scaled back by setting the model in accordance with the full size arrangement. Those results can be used for inferring the conditions for best performances of the actual application.

As previously stated in section 2, some parameters are fixed by standards and the technology chosen: type of paint and type of application; air pressure; end-tool trajectories; paint flow through the aerograph's nozzle; distance from the wall. Instead the speed of arm motion and distances between two lines of the trajectories were left to vary: velocity between 0.0363 and 0.11 m/s; distance step between 0.04 and 0.05 m. The two variables used to express the quality of painting are:

- **saturation:** indicates color purity and intensity;
- **thickness uniformity:** indicates the thickness variation on the wall surface, that must be as constant as possible in order to avoid that visual perception changes with respect to the direction from which the surface is perceived.

The first was measured using an image processing software, restituting how far from the totally 100% saturated condition is a surface after one or more coatings. The second is important to avoid that too big variations of paint thickness on the surface could cause a particular reflection of light that is perceived by human eyes as a (vertical or horizontal) stripped surface, like in case of application of only one coat. The final model must guarantee to obtain the desired level of saturation together with the necessary thickness uniformity.

The first step consists in working out the mathematical relation between saturation and motion speed of the robot arm. A sample of three strips, painted at three different velocities, namely 0.036 m/s, 0.073 m/s and 0.11 m/s, was created.

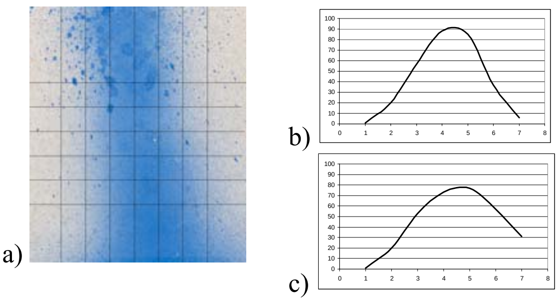


Fig. 5: sample for saturation measurements (a) and examples for the courses relative to the first (b) and fifth (c) cross sections starting from the top.

For each case six measures of saturation level were executed along cross sections like in Fig. 5-a (showing the painted strip obtained through a motion speed of 0.073 m/s) and saturation diagrams were built, like the ones in Figg. 5-b and 5-c. Hence a statistical sample of 18 saturation measures was available, dependent with speed. The repetition of six measures for each case was necessary to manage causal errors inevitably affecting experimental tests. From each set of six curves referred to every value chosen for speed, it was inferred the mean and the two extreme diagrams embracing the 68.26% of the likely saturation distributions [9], that are given by the mean added or subtracted by an amount equals to the standard deviation of each saturation curve. Such an operation was made feasible noticing that the distribution of these curves resulted as normal by the outcomes of Jarque-Bera tests [10]: it is a statistic for testing whether a series is normally distributed. The test statistic measures the skewness and kurtosis differences of the series with those from normal distribution: under the null hypothesis of normal distribution the Jarque-Bera statistic is distributed like a χ^2 (chi-square) with 2 degrees of freedom. In the case of this paper the null hypothesis was never refused. These curves were used to infer the most probable range for each speed value and then the final saturation deriving from their superposition and the study of thickness uniformity. But an intermediate necessary step is the one relative to the generation of droplets: if too much paint flow is sprayed on the wall surface, droplets could be formed and as a consequence a poor quality work would come out. In other words it is not possible to paint with very low speed and high paint flow on the wall, because it would generate droplets.

That problem was overcome through the generation of another statistical sample of 10 data. Ten small pieces of plaster board were sprayed from a distance of 0.08 m until droplets were generated (Fig. 6). Obviously it was not possible to interrupt the flux in the exact moment when is starts dropping, therefore further elaboration was necessary: the time lasting from the opening of the nozzle to the generation of the first drop was filmed and then measured. The weight per unit of surface of the paint flow on the surface generating drops was computed, starting from the knowledge of the volume of paint thrown on the surface (dependent with the flow through the aerograph that is known *a priori*), the whole surface covered by paint and the ratio between saturation levels on the points of the covered surface (using the aforementioned image processing software).

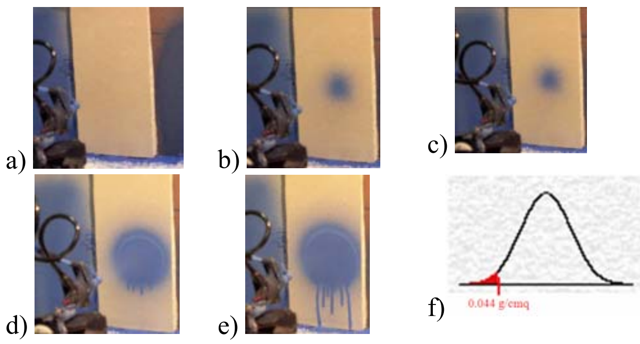


Fig. 6: some frames of the spraying for droplet analysis (a-e) and final statistical distribution with the lower 1% quantile marked (f).

Also in this case the null hypothesis of the Jarque-Bera test was verified, meaning that Gaussian distribution was correct for the available sample depicted in Fig. 6-f, where the lower 1% quantile is marked, that is the prudential value assumed as starting point for droplet triggering. These data were integrated with those ones collected with the experiments summarized in Fig. 5: using a procedure similar to the one just described, the amount of paint per unit of surface was computed and linked to the corresponding saturation values. As a result, a diagram where saturation is expressed over paint flow per unit surface is obtained like in Fig. 7: it highlights the point meaning the maximum amount of flow allowed to be sprayed ("Droplet generation"), whose value cannot be exceeded during painting.

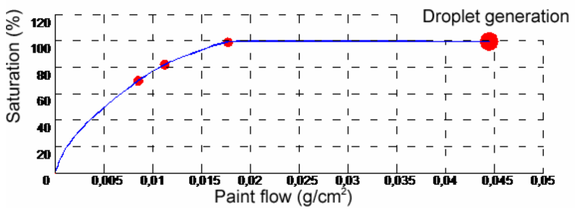
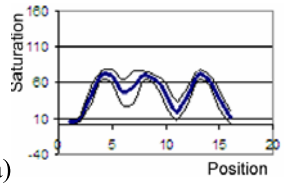


Fig. 7: Final diagram with the condition of droplet generation.

Previous to writing the final mathematical form of the empirical model, it was necessary to analyze the other problem, connected with thickness uniformity. It is clearly dependent with the distance step between two different lines of the same trajectories: if its chosen value creates painted coats whose thickness varies inside a too wide interval, the final colored layer could be perceived by people as stripped, instead of uniform, due to the different reflection to which light is subject towards the half plane observed by the receiver. A parametric analysis was carried out, varying the distance step between two lines of trajectories for each motion speed previously considered. Results similar to the ones in Fig. 8 were obtained: case *a* is an example of not feasible solution, while case *b* is a good example. It must be remarked that the three lines of every diagram are relative to the saturation mean (bold solid line in the middle) and to the two extreme diagrams (thin solid lines) where the 68.26% of trials will fall. A statistical sample was built with the following procedure: every saturation diagram previously computed corresponding to every speed value (0.039 m/s, 0.073 m/s and 0.11 m/s) was superimposed at distance steps of 0.04 m, 0.045 m and 0.05 m, obtaining other curves of the kind depicted in Fig. 8. Every case where variation is too high, like in case of Fig. 8-a, was eliminated from the sample and the remaining data were adopted to compute the final empirical model.

a) 

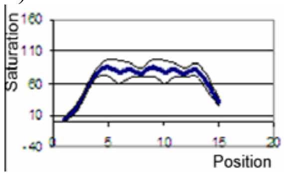
b) 

Fig. 8: Analysis of superposition for different distance step values, speed and distance from the wall.

It is worth pointing out that it is not correct to paint a surface applying only one coat, because it would generate a stripped surface, whose thickness variations would be systematically distributed. Instead a superposition of at least two coatings is advisable, to avoid systematic textures of the paint distribution that could be perceived by human observes.

Utilizing the data collected, it was possible to work out a statistical model, through the application of the Multiple Regression [10], that exploits the OLS method to compute the model that is the best approximation of the data at disposal. Its final version is:

$$Y = 189.84 - 7.04 \cdot x_1 - 13.6 \cdot x_2 \quad (1)$$

Where Y stands for saturation, x_1 is the distance step between two lines of the trajectories (between 0.04 and 0.05 m) and x_2 the speed (between 0.0363 and 0.11 m/s). Fig. 9 shows that residuals are very small and their covariance is quite null, confirming the good choice for this kind of model.

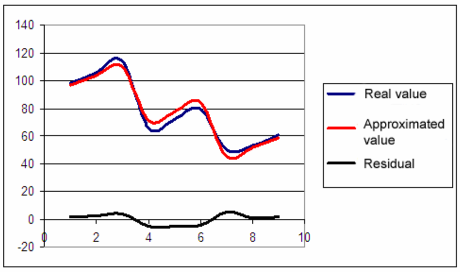


Fig. 9: Residuals of the approximated model.

3.3 Description of Experiments and testing

Experiments were performed to validate the model developed in section 3.2:

- inverse kinematics was applied to drive the end-tool (aerograph) along the path shown in Fig. 1-c [11], holding the aerograph at a constant distance (0.08 m) from the wall and its nozzle perpendicular to that surface;
- a rectangular surface 0.4 m by 0.4 m large was painted with a distance step of 0.04 m;
- saturation of the painted module was measured and then compared with the theoretical one;
- the same previous steps were repeated for the case of the trajectory in Fig. 1-b;
- the two previous coats were superimposed to verify the quality of the final work.

Fig. 10 shows the robot painting process of the wall according to the trajectory of Fig. 1-c, whose final aspect is shown in Fig. 11-a. The model of eq. 1 forecasts an average saturation equals to 84.3% (when the distance step is 0.04 m and speed is 0.0726 m/s); by measurements it came out that the real average value is equal to 86.7% , with a very low shift of 2.4%. The case of Fig. 11-b was obtained painting according to the trajectory in Fig. 1-b and for the same previous values of independent variables, obtaining a measured saturation of 87.3%, having a shift from the real value equals to 3%. In both cases the model is shown to be very reliable, therefore it can be considered opportune for painting quality forecasts. Finally the quality of a two coat painting (Fig. 11-c) was evaluated to verify the good choice of the two trajectories, and the final result was shown to be in accordance with the forecasts, where the saturation level is equals to 100%.

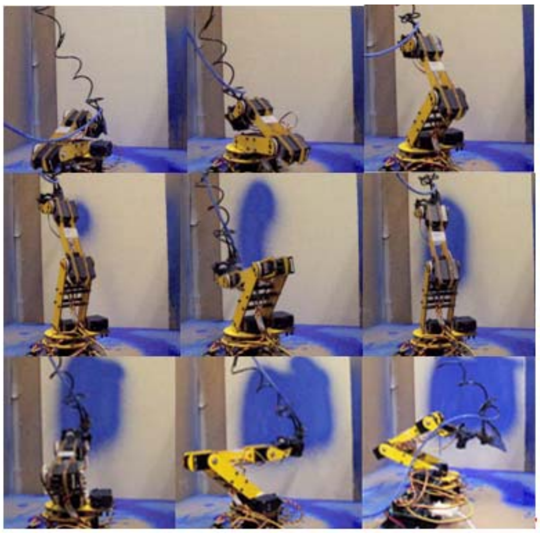
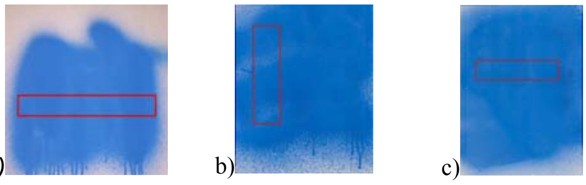


Fig. 10: Frames relative to vertical path painting.



a) b) c)

Fig. 11: Paint quality for one coat of vertical (a) and horizontal (b) painting and after two paint coats (c).

4. CONCLUSIONS AND FUTURE RESEARCH

The first encouraging result obtained from this work is relative to the feasible approach of the scalability of the problem: it allows to perform experiments with lower waste of raw materials, power supply and maintenance costs. Some complex arrangements of construction sites will be reproduced in future research and then robotized painting will be verified with particular attention to every parameter affecting the quality of the final work.

To enhance the emulating possibilities of the scaled robot version, it will be equipped with other types of end-tools, like airless and mixed air spraying types. Their behavior will be again formalized and then compared with the full scale one, building empirical or analytical models like the one developed in paragraph 3.2, valid for both scaled-down and full size robotized equipments. Hence it will be possible to relate the quality of the work coming out from the scaled-down procedure with the one performed at full size. To accomplish this task it is necessary to individuate every parameter that affects the paint quality, and reduce it to small size. In this paper it was shown that an empirical procedure is available to build mathematical models for painting quality when analytical relations are not available, and its accuracy is demonstrated by the good matching with experimental results. Future research will be devoted mainly to check other models for different kinds of application relative to both different spraying techniques and to more complex construction sites. Moreover the full scale laboratory will be set, equipped with a robotized machine (Pollock #2) with the same degrees of freedom of the scaled one and end-tools corresponding to the ones used for the scaled version.

Sensing strategies will be tested, taking care to the correspondence between scaled-down and full size sensors and to the possibility to reproduce in reduced size every problem that could occur in an actual construction site. When these two laboratories are set, it will be possible to test a highly autonomous robot in scaled construction sites, optimizing all the electronic and algorithm strategies to let it orientate and navigate throughout environments which are not *a priori* known. When control strategies are tested, final full size experiments will be performed in the 1:1 scale laboratory or in actual construction sites.

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