COMPUTER-VISION CONTROL FOR A FLOOR-TILING ROBOT

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ABSTRACT

At this stage of the floor-tiling robot's development it was decided to concentrate on the autonomy at a workstation, which means that all operations at a workstation - stabilizing and calibrating at a workstation, loading tiles, etc. - including real-time quality assurance (QA) are done without human intervention, while the transfer between workstations is assisted by an operator. The QA function has to identify the exact location and orientation of tiles to be taken, since they may be expected to differ from those specified in the robot's program. This is needed in order to allow accurate setting of the tiles in straight lines and with a uniform distance between them. Additionally, the QA function has to identify defective tiles. A computer vision system was developed to perform the QA functions. The prototype, its operational principles, and the experiments are described.

1. INTRODUCTION

After completing the development of the multipurpose interior finishing robot's pre-prototype [8, 10], an interior floor finishing robot is being developed at the Technion - Israel Institute of Technology. This robot is called a Surface Horizontal Autonomous Multipurpose Interior Robot (SHAMIR) [4]. The conceptual development of this robot's first module for floor tiling, and its computer-vision-control system are described in this paper.

A number of floor treatment robots have been developed, mainly in Japan [e.g. 1, 2, 3, 11]. Almost all of these robots were intended for concrete floor processing purposes, such as screeding, grinding, and brushing [9]. At the time of writing, no floor tiling applications were known.

More relevant to the present work is the (wall) tile setting function of TAMIR, an anthropomorphic multi purpose interior finishing robot [7]. The tiles, supplied in boxes, are placed beside TAMIR, which picks them up with a vacuum gripper, each tile being held approximately at its center. The tile is taken to a gluing station, where it is released into a reclined rectangular corner for two purposes: (i) to receive the glue and (ii) to be picked up again in the exact required position and orientation. TAMIR then takes the tile to its setting location, where it is pressed evenly against the wall until it merges with the predefined surface of the tiled area. A delay of several seconds before the vacuum is released enables the glue to set, so that the tile will not slip down.

A good understanding of the manual work is needed as a background to automating the corresponding task - floor tiling in the present case. Consequently, a field study was conducted to investigate the manual process thoroughly. The study included observations and work sampling to measure the work inputs in the manual work.

The work inputs of the manual work vary according to the size of the tiles, the size and shape of the rooms, etc. Therefore synthetic work inputs were measured, i.e. the durations for each sub activity were measured separately. This enabled a detailed analysis of the work inputs for various sizes of tiles and different rooms. The resulting work inputs of the manual work vary from 0.47 hr./m^2 for a 3.00 m by 4.00 m room and tiles of size 20x20 cm, to 1.42 hr./m^2 for a 2.60 m by 2.60 m room and tiles of size 10x20 cm.

2. THE FLOOR TILING MODULE

The development methodology of the multipurpose interior finishing robot [8] was adopted for the floor tiling robot. The conceptual development consisted of the determination of performance specifications, robot design, and modeling it with a graphic simulation system, as well as measuring the robot's performance.

2. 1. Performance Specifications

It was assumed that the work environment of the robot is the closed frame of a building erected by industrialized methods. The reason for this is the higher accuracy achieved by industrialized methods, which are a precondition for robotized work. It was also assumed that due to its expected size, the robot will be mainly operating

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in large halls. The halls will either be open spaces within the exterior walls, or they will include interior columns. In any case, partitions will preferably be erected after the tiling task has been completed. Such partitions, drywall for example, are very common today and have additional advantages such as flexibility in design, ease of effecting changes in the interior layout during the life cycle of the building, etc.

SHAMIR's concept was based on two modules, 'work' and 'mobility'. The latter module serves all tasks and includes an independent power supply unit, a propulsion unit, and the main controller. The work module includes the robot's arm (if any), the end effector(s), the sensors, and the material supply system. The work module is task-specific, either for one task, or for a number of them, differing mainly in the required end effector, control algorithms, and sensors.

The combined weights of both modules must not exceed 400-600 kg, so that the floor, which is designed for limited live loads, is able to bear them without having to be specially strengthened, or without recourse to additional reinforcement, or extra support. The maximal measurements of both modules together must not exceed 0.7x1.0 m and a height of 1.8 m, so that, if the robot has to move through doors from one space to another, it can do so without a change in the accepted measurements of doors.

The robot must be able to operate in an autonomous mode while at a workstation. Its movement between workstations and some preparatory and completion tasks, on the other hand, can be done by, or with the assistance of, its operator. The requirement for autonomy at a workstation demands that it has to lay the tiles in straight lines with uniform distances between neighboring tiles, and that it has to check that the tiles are not defective. In order to do so, the robot must neither have recourse to spacers, as is done in the manual work, nor rely on operator involvement, while operating at the same workstation.

2. 2. Robot Design

The robot has two modules, a work module and a mobility module. In contrast to the previous concept, presented in [4], the work module is above the mobility module. The previous concept was governed by the robot configuration, which had to allow the gripper to pick the tiles up accurately in order to place them precisely. Because of this, the tiles had to be stored in special magazines on a turntable. The present concept permits a simpler design, because the accuracy of picking up the tiles is assured by using a computer vision system. This modification of concept does not change the multi-functionality of the robot, as it still has separate work and mobility modules.

At this stage of development, it was decided to concentrate on the autonomy of the robot only at a workstation. Thus the robot and the operator work as a 'team'. It is the authors' belief that this approach is more practical in the short term. As a result of this decision, the work envelope of the robot had to be extended in order to minimize the percentage of the unproductive time resulting from the movement between workstations. That extension is achieved here by adding a rotating plate between the mobility and the work modules. The plate enables a 90° change in the robot's orientation each time. Once such a turn is completed, the robot position is fixed by means of a pin which enters a hole in the plate designated for it. Thus the robot's effective work envelope is tripled, and in some cases even quadrupled.

The supply of raw materials - tiles and glue - must be continuous. Two alternatives for the supply of tiles were considered, to have either the tiles stored on the robot, or supplied on pallets to the vicinity of the planned workstations. Having the tiles on the robot affects the limited dimensions and weight of the robot. Additionally, it requires either on-line human involvement for replenishing the stocks, or an additional service robot for this task. The pallets in the vicinity of the workstations may (i) introduce serious problems of maneuverability and navigation, (ii) present difficulties with calibrating the robot at each workstation, and (iii) require a longer arm with more degrees of freedom (DOF). Consequently, as it is assumed that an operator is available, which means that he/she can prepare the next pallet before the current one is consumed, the alternative of the tiles being stored on the robot was chosen.

The mobility module includes the propulsion system, i.e. motors, transmissions, and wheels, and the power supply. The work module includes, in addition to the tiles and the tile-setting system, a container of glue, and the control system. The power can be supplied from batteries, by an engine-driven generator, or by a cable plugged into an outlet on a wall or above the robot. The batteries, or the generator, have to supply power for 4-8 hours of continuous work, before recharging or refueling.

The main task of the control system is real-time process control based on data received from sensors (in this case a computer vision system). The system controls the arm's movement, activates the sensors, processes the data received from them, controls the vacuum gripper and the gluing nozzles, etc.

The robot's arm has six DOF, enabling it to reach all necessary locations, with the needed orientation. The first three DOFs allow motion of the entire arm in space, while the last three account for the orientation. The shape of the links was determined in a way that would enable minimizing their weight considering the required accuracy level.

Three main alternatives for the end effector were considered, all having a vacuum device for gripping the tiles. In the first alternative the tiles would be supplied with dry glue on their backs. Once they have been placed on the floor in the right location and orientation, a special tool would cause the glue to liquefy and the tile to stick to the floor. Such a tool could operate on various physical principles, such as heating, microwaving, etc. This solution meaningfully simplifies the robotic work by eliminating the gluing phase, and it is a cleaner solution. On the other hand, it is still somewhat premature and would therefore require some technological development effort. Consequently it was postponed to the prototype development stage. In the second alternative the tile would be taken to a gluing station, the glue would be applied, and the tile would be taken to its setting position. This solution, which was successfully tested by [7] and described in the Introduction, uses additional arm movements and thus increases the robot's work inputs. The third alternative uses dispensers attached to the gripper. They are moved underneath the tile just when it is above its setting location and dispense the glue. This was the alternative adopted.

2. 3. Performance Analysis

The robot development, as described above, had to be examined in order to (i) understand the way the proposed robot operates; (ii) check its performance and compare it with the specifications; (iii) assure the logic of the tiling program; and (iv) check that the robot's arm does not collide with the existing environment, namely the building elements (walls, columns, etc.), the components of the robotic system itself, etc. Based on previous experience [4, 6] it was decided to use graphic simulation for this purpose. The simulation system used for the present research is based on a software package called Robcad® (by Tecnomatix), which runs on a Silicon Graphics workstation - Iris®.

The parameters of the simulation for the work outputs measurements were:

- Movement from one workstation to the next, based on previous analyses and experience [5, 10]: 1- 4 minutes.
- Maximal joint speed: 1.0 m/sec. for prismatic joints, and 90°/sec. for rotational joints.
- Speed of the rotating plate between the mobility module and the work module: 5-10°/sec.
- Tile size: 10x20 - 20x20 cm.
- Number of tiles placed in each setting cycle: 1-3.
- Vacuum gripping: 1 - 2 sec.
- Glue spraying time, and the time needed for pressing down the tile (once set down) to assure good bonding: 5 - 15 sec.
- Room size: 2.60x2.60 m - 3.00x4.00 m.

The simulation results of work outputs varied between 1.6 m^2/hr. to 11 m^2/hr.

The authors' experience shows that the development of a new construction robot is a multistage process involving numerous issues and problems to be solved. The development of the present robot, as described above, still leaves a number of problems to be solved, some of which will be dealt with at the prototype development stage. These include (i) stabilizing and calibrating the robot at each workstation, (ii) eliminating the gluing phase, making robotized tiling a single-phase operation, (iii) quick loading of tiles on the robot; (iv) reduction of the robot's weight, (v) finishing work that the robot cannot do, or areas it cannot reach, and (vi) real-time quality assurance (QA).

At this stage, the real-time QA seems to be the most crucial problem on the way to making the proposed robot technologically feasible. This includes (i) setting the tiles in straight lines with exact and uniform distances between them and (ii) assuring that the tiles do not have defects (cracks, chips, stains, etc.). The first component of the QA is easily solved if the tile is picked up exactly at its center of gravity (CG) and with its edges parallel to the tool frame - i.e. in the correct orientation [7]. If this is achieved, the robot can precisely set the tiles in the required pattern, based on the tiling program in its control system. There are two reasons why the tiles should not be checked for defects before they are loaded on the robot. Firstly some of the defects can be caused during loading (and even after it), and secondly checking them in advance would require depalletizing, inspection, and repalletizing, which are labor-intensive and/or time-consuming.

It was assumed that both components of the real-time QA could be achieved with a computer vision system attached to the robot. Consequently it was decided to concentrate the first hardware development effort on investigating this issue.

3. The Computer Vision System

3. 1. Objectives

Real-time QA is needed to overcome the many inaccuracies prohibiting the precise setting location of each tile and to make the tiling operation at a workstation fully automated. The QA includes the setting accuracy and making sure that each tile, to be set by the robot, is not defective in any way. Possible defects are: chipping, cracks, broken tiles, etc.

The difficulty in achieving real-time QA is not only due to the required setting accuracy and the need to identify defects, but also because the location and orientation of the tiles to be taken on the pallet normally deviate from the theoretical data specified in the tiling program. It seemed appropriate to solve the problem of real-time QA for this operation with computer vision. Because of its importance to the floor-tiling robot, it was decided to build a prototype system and experiment with it. The experimentation system is by no means an ideal comprehensive solution to the problem, but rather a proof of the concept, and an attempt to identify problems. The performance requirements of the system, in each tile setting cycle, were (i) to identify the location and the orientation of the tiles to be picked up by the robot; and (ii) to identify defective tiles.

3. 2. The Experimental System

The system comprises the following components: A controller, which receives the data from the Video Signal Input Card (VSIC), processes it, and renders it into robotic commands; a monochrome VSIC with 255 gray level resolution; Monochrome Video Camera (COHU); and a six DOF Robot (MANTEC). Fig. 1 shows the robot arm, the camera, and the gripper.

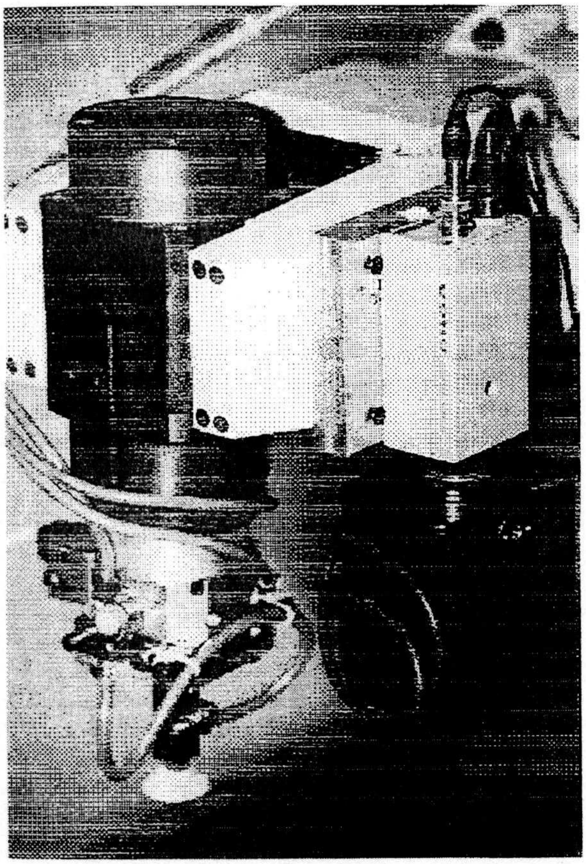

FIG. 1: A close look on the experimental system

There were two work areas, one of which contained the tiles to be picked up (depicted in Fig. 2), the other was the setting area. An experimental cycle included the following operations:

- Moving the robot's arm to a position above the planned location of the next tile to be taken.
- Operating the camera.
- Activating the real-time QA module.
- Calculating the exact location and orientation of the tile.
- Commanding the robot to pick up the tile with the gripper at the tile's exact CG (center of gravity), and with the edges of the tile parallel to the tool frame axes.
- Based on this information:
  - if the tile is defective, moving it to the stack of defective tiles,
  - if it is O.K., moving it above the planned setting position.
- Commanding the robot to set the tile.

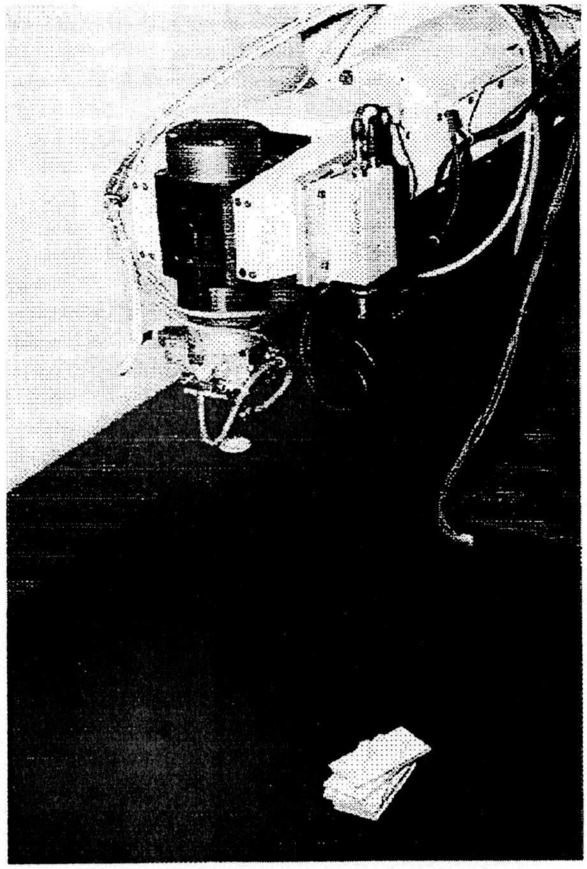

FIG. 2: The robot, the vision system, and the tiles

3. 3. The Video Input Processing

The data received from the video camera is used to perform the real-time QA by calculating variables such as the tile's CG coordinates, its orientation, its area, and its moments of inertia. The real-time QA also includes checking the tiles for defects and assuring that the tiles are picked up precisely with regard to their CG and orientation. Based on previous experience [7], picking up the tiles accurately assures that they are set in straight lines with constant uniform gaps between them.

The camera was attached to the arm with a permament fixture. There was no relative motion between the camera and the arm (in order to simplify the experimental system). When reading the tiles' information, the camera had to be relatively low, and when the tiles were picked up, relatively high in order to protect the camera from being damaged. This was achieved by carful planning of the motion of the arm. Fig. 3 shows a digitized image of the two positions.

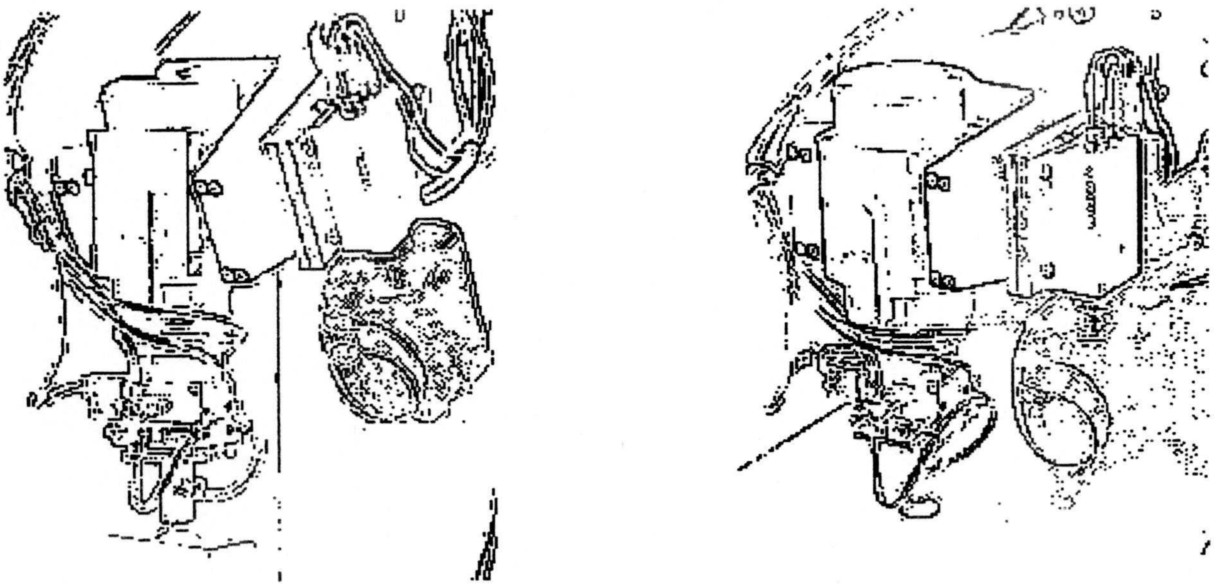

FIG. 3: The camera's fixture to the robot's arm in an approaching and in a reading positions

The VSIC keeps the data of any given picture in a 512x512 matrix format. The information includes the coordinates of the pixels, and their gray level, on a scale ranging from (theoretical) absolute black (0) to absolute white (255). The first stage consists of scanning this data and classifying each pixel as either black or white - binary picture - based on a preliminary calibration. In our case we used strong and stable lighting conditions and assured contrast between the tile's background (black) and the tile itself (white). Consequently the thresholds for classifying the pixels were: 225 and above was defined as white, 30 and below as black. Based on this, a binary picture was generated, which served as the basis for all subsequent calculations, most of which involved counting the number of white pixels (which represented the tile).

3.3.1 Center of Gravity Determination. The area of each tile was checked by comparing the number of its pixels to that of a 'standard' tile as measured at the calibration stage. The calculation of the CG was based on a relatively simple algorithm. While counting the number of pixels for the area calculation the x- and y-coordinates of the white pixels were summed to produce two variables. The x- and y-coordinates of the CG were calculated as the product of the sum and the area (i.e. the number of white pixels). These calculations were made a number of times, and the maximal discrepancy between them and the real CG turned out to be under 1%, which is a satisfactory result.

3.3.2 Orientation Determination. Two algorithms for the calculation of the tile's orientation were tested. One determines it by calculating the angle between two lines - a reference line and one of the tile's edges, scans the binary picture, and erases every white pixel that does not have a neighboring white pixel. Next, it determines which pixels are on the same line and performs on them a regression to determine the exact line. The other algorithm finds the tile's moments of inertia and, on the basis of this, their axis of symmetry.

It was found that the second algorithm was significantly more accurate, especially when there were difficulties with the lighting conditions, Namely when the changing light level caused changes in the number of white pixels. These changes constitute a higher percentage in the first algorithm than in the second, which uses all the white pixels of the tile.

3.3.3 Defective Tiles Identification. The identification of defective tiles was based on the calculations made for two previous purposes, namely the location and the orientation. Two criteria were used: the tile's area and its moments of inertia. The area test alone was not sufficient, for the following reasons:

1. Broken tiles in which all the broken parts are not too far apart would still have almost the same calculated area as an unbroken one.
2. Changing lighting conditions may cause concealment of white pixels because the threshold value determined

for white is a light-dependent parameter. As a result the calculated area may change.

3. There are inherent inaccuracies in the production of the tiles themselves.

Combining the two criteria reduces the uncertainty of testing because the moments of inertia take into account not only the area, but also the way it is laid out. Thus, the broken tiles described in 1 above did not pass the QA test, on the strength of their moments of inertia.

4. SUMMARY AND DISCUSSION

The development of the floor finishing robot included determination of performance specifications and designing several alternatives of the robot. The alternatives were modeled with a graphic simulation system, which enabled checking their performance and predicting their work outputs. The minimal work inputs of the robot is expected to be 0.09 hr./m^2 and the maximal 0.62 hr./m^2, which is equivalent to work outputs between 1.6 m^2/hr. to 11 m^2/hr. The work inputs of manual tiling (for similar tiles) vary between 0.47 and 1.42 hr./m^2, which means that the robotic work outputs in tiling is expected to be 2 - 5 times higher than that of the manual one. In other words: a 'team' of one robot and one person can replace 2 to 5 persons.

A computer vision system was developed to perform real-time QA The system identifies the exact location of the tile to be picked up, and its orientation, which also permits precise setting. At the same time the system checks if the tile is not defective, by using area and moments of inertia calculations. If the tile is found to be defective, the robot moves it onto the defective tiles pile; if it is complete, it is set in the prescribed location and orientation on the floor.

At this stage the development of the robot focused on defining its concept and designing its components. It was restricted to issues arising from the robot's autonomous performance at a workstation, assuming that in the first stage it would need an operator to assist in stabilizing and calibrating the robot, once it arrives at the workstation, in loading tiles on the robot, in finishing areas that the robot cannot reach (e.g. small rooms or niches), etc. Some technological issues were also left to the next development stage - prototype development - such as eliminating gluing.

The computer vision system was built in order to prove a concept. Clearly, such a system has limitations, which will be briefly reviewed below.

The present system is two dimensional, and consequently it could not deal with a stack of tiles (as shown in Fig. 2), which is the standard and logical packaging method. Future research will have to use three dimensional computer vision for a tiling robot. Additionally the system used in the present case was monochromatic, and consequently stains and defects in color could not be identified.

Probably two of the more difficult problems to overcome on a real-life construction site are the changing lighting conditions and the dusty environment. In the lab we maintained stable lighting conditions and assured a contrast between the tile's color (white) and its background (black) to overcome the lighting problems. A part of this solution may be adopted to solve the problem on a construction site, namely to use a strong light source mounted parallel to the camera and overriding natural light. The problem of dust may be solved to some extent by blowing air to clear the camera's 'line of sight'.

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