In-process automatic quality control and product characterisation system
for traditional ceramics s

Abstract

The project aimed to develop innovative and cost-effective in-process control technology for the critical stages of ceramic tile production, including, as a major development, the final quality assurance stage in order to improve product quality and process knowledge, and reduce material waste. The industrial problem being addressed was that in a climate of world overproduction in ceramic tiles, quality and price are the two key factors on which European tile manufacturers can compete effectively.

To this end, the project aimed to develop automation and sensor based control techniques that can deliver consistent quality and provide costs savings. The main development areas are listed below: ! .

- Development of an intelligent in-process quality assurance system for the finished products
- Des!gn and development of a complete in-process monitoring system for feed-back control for all critical stages in the manufacturing process
- Development of new mechanical handling and transport equipment responsive to automatic, in-process monitoring and quality control
- Computer Aided Design (CAD) link to tile decoration and fin'al QA

The quality assurance system is a hybrid vision system for surface characterisation of ceramic tiles. Major developments were in the areas o;:
- Vision algorithms and expert analysis of product quality characteristics
- Hardware with minimum data bandwidth of 3.5 GB per second
- Optical instruments for 3D surface fault detection and surface planarity

1, Introduction

A ceramic tile is made from a pressed clay biscuit which is either coated with a ceramic glaze . *or* left in its natural state. This product is fired in a kiln to make it hard and waterproof. Decoration can be applied to the tile after it is coated with its background glaze and before being fired, or form part of the 'body' in the case of unglazed products.

After firing and cooling tiles are manually inspected for defects in both the decoration and the tile body. Inspection can be performed at up to two tiles per second for simple tiles and can be as slow as one tile every fifteen seconds for large polished floor tiles.

The list of processes involved in ceramic tile production is large and for the sake of a clear overview a schematic diagram of production organisation for ceramic tiles is given in figure 1.1. Only key processes are illustrated.

Processing is stil[based generally on a strict division of the various production steps, Between these procedures the tiles are stored. it is wfell known that storage is undesirable because it involves extra handling time, it takes up valuable space, it causes soiling and it leads to excessive breakage.

A more serious difficulty however is that this type of production method makes it impossible to either track continuously a particular product or close the control loop since by the time a product is being sorted som e of Ihe production phases have already been completed.
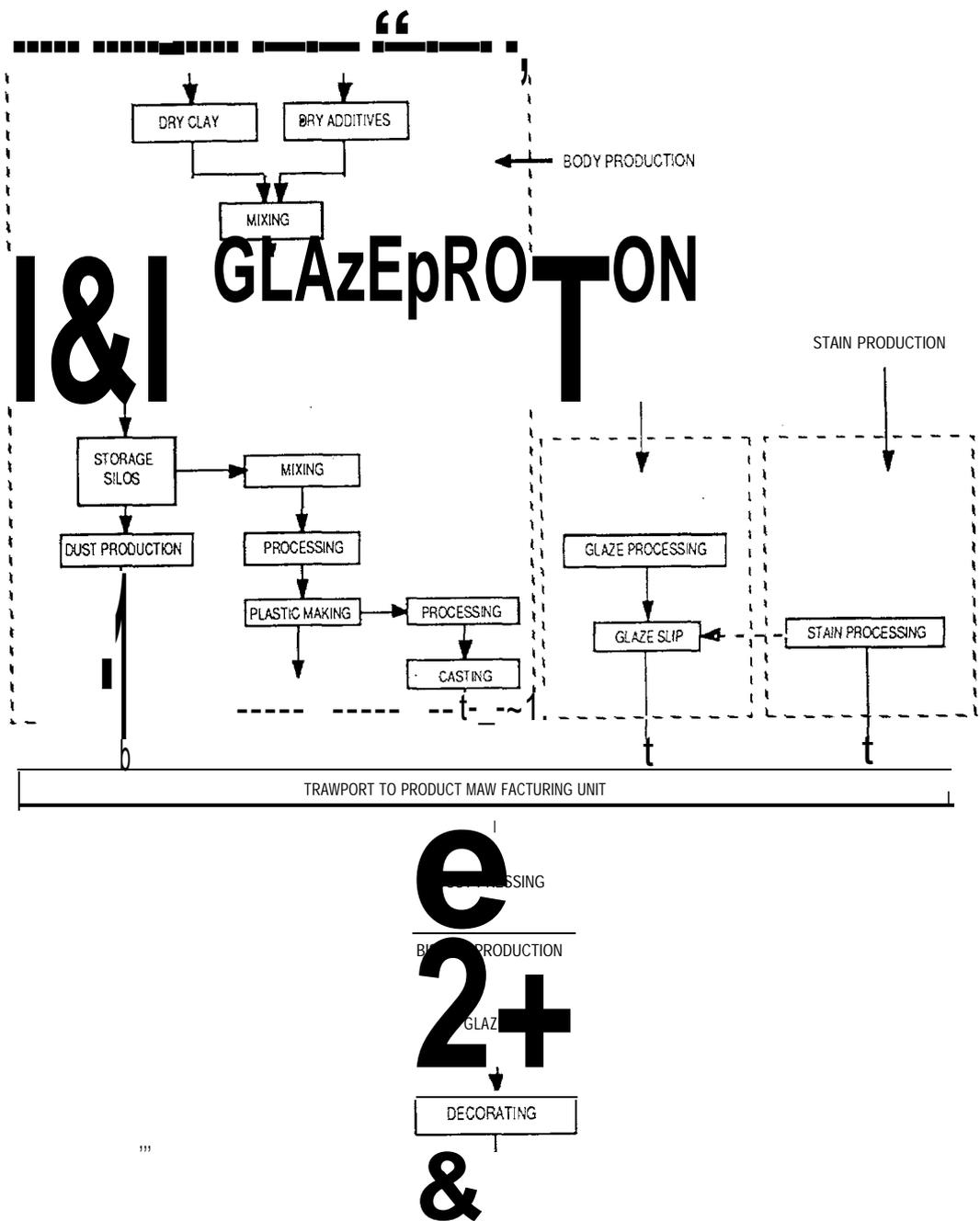
Figure 1.1.   Production organisation for glazed ceramic tiles

2.   Overview of technical developments

2.1.   Development of the quality assurance system for finished tiles

2.1.1. General
The consortium started the project with a good knowledge of the ceramic tile environment and the fundamental principles and technologies rewired to achieve the objectives. At the start of the project a precise specification of p;oduct quality was attempted "in order to relate the

dependence of quality characteristics to process parameters. Il was soon realised that there is no accepted standard and an absence of quantitative information on which to base such specification. Even more serious is the lack of means to obtain such information.

An important firts task was therefore to define product quality characteristics and build a data-bank from a variety of different products which when analysed wouJd provide a basis for deriving a more precise specification. To this end the QA system was developed early on and iristalled on a production line to obtain relevant data prior to proceeding with the final design of the monitoring and control system. This first pilot proved to be entirely inadequate lor obtaining Ihe required quality information. H was also obvious that to achieve a satisfactory result development should take place with the constant feedback of tile quality experts. Further development was therefore undertaken within a tile manufacturer's premises, lasting about one year, at the end of which the desired result was achieved.

A major part of the project was the development of the automated quality control and surface characterisation system for finished products. There are two distinct operations required by such a system; defect detection and surface characterisation for 'batch grading',

Considering that tiles are products which must no{ necessarily be identical but simply conform to a qualitative aesthetic standard, the problem facing any in-process quality assurance system is the ability to assess on a human basis what variations constitute defects and what variations constitute desirable or acceptable characteristics.

Defects are simply non-desirable characteristics that have a detrimental effect in the perceived quality of the product where all other variations are either desirable or accepted process variations that do necessarily occur but must be detected and batched appropriately.

The Q.A. system developed was an intelligent hybrid vision system, capable of surface characterisation and defect detection on-line. Design considerations had 10 incorporate additional constraints resulting for the fundamental requirements of ease of use for shop-floor employees, expertise in quality characteristics, robu.!ttness for operating in a harsh environment and qualitative decision making adaptable to different products and manufacturer requirements.

The system incorporates two main components. One for physical defect detection (SFD) and another which allows photometric surface characterisation (Textone) . Some of the physical characteristics can oniy be detected using special viewing conditions and cannot be observed using the same techniques appropriate for photometric characteristics. The two systems are designed to be integrated and operate from a single console which incorporates a touch screen and a graphical user interface.

An accurate imaging system can only reliably operate in a reasonably clean and constant envircmme~t. The tile production environment is very dusty and has widely fluctuating temperatures. It was therefore necessary to hermetically seal the system and use a heat exchanger to control the internal temperature.

Textone analyses the photometric characteristics of the surface,, and it has special facilities to achieve this. The resultant image data available in Textone allows surface characterisation and grading to take place and also edge analysis, sizing and photometric defects.

SFD utilises special lighting and optics to produce a surface map of the tiles passing through the system. This allows it to detect three dimensional variations on the surface of the tile which are not generally visible to Textone. These variations require interpretation by the systems' computers and variations must be put in the con!ext of the tile's usual finish.

2.1.2. Textone

'Grading' is an ill defined ta$k because aes!hetic qualities of complex surfaces cannot be reduced to a simple set of quantitative parameters for all types of surfaces. It is also crucial that the system can operate with any lype of surface. This has been accommodated by incorporating a teach by example training strategy. From these examples, the system performs an extensive analysis to determine which characteristics distinguish the various grades and what the bounds for these characteristics are. To accommodate this various classification processes have been researched, in particular neural networks and fuzzy logic systems. Neural networks have proved inappropriate particularly in view of small sample sizes favoured in continuous production environments. A fuzzy logic classification process is utilised coupled with graphical representationsof the feature space extracted from each surface. The graphical representation allows modification of training pararnetersand to mcorpora;e grades not present during training.

The Textone system emulates the complex pre-attentive visual process employed by humans during operations such as sorting.

Two key aspects of the Textone system are the grey-level stability , and the camera system. Grey level stability is absolutely cruciaJ to the system and several Techniques have had to be developed in order to provide the system with the required level of stabihty. These techniques are required for all components in the analogue domain and al! analogue devices have closed loop feedback control.

The camera requirement is very stringent as its demands high resolution along with high sensitivity, large dynamic range and low noise. Current camera technology which achieves these goals is inadequate. Modifications in existing camera technology have been implemented and the performance optimised as far as possible. An investigation into the feasibility of incorporating these features has lead into a new design of camera.

2.1.3. SF?)

SFD utilises special lighting and optics to produce a surface map of the tiles passing through the system. This allows it to detect three dimensional variations on the surface of the tile which are not generally visible to Textone. These variations require interpretation by the systems' computers and variations must be pu{ in the context of the tile's usual finish.

The system works on a wide range of tile surfaces up to an including 60cm wtdihs. Almost all of the separation of defects from correct tile surface is accomplished by optical techniques. However, shape analysis of the surface features is necessary to detect genuine features from 'noise', For example a certain amount of small, random pits may be acceptable, but if those same pits were localised and joint into" a line they become a scralch which is not acceptable. Shape analysis is a very computationally intensive task and so a special parallel processor board has been designed to provide the power to accomplish this task.

The lighting and optics require accurate alignment and must be realigned for different surface finishes. This necessitated that many of the alignment movements be motorised. SFD can map surface characteristics of most surface types.

Defects of 30pm wide can be detected but only when they have a particular orientation with respect to the direction of the illuminating beam while the resolution of the system for the particular viewing angle is 310pm. In general it was found that:

* Scratches are best detected when their orientation is perpendicular to the direction of illumination beam. In such cases scratches ten times smaller than the system resolution can be resolved. Scratches at other orientations are sufficiently well resolved.

. Illumination **angles** <87° are suitable for all tiles, while angles up to 80° can be used for opal and glossy tiles, resulting in sharper images.

The results are important andnovel. There has been no significant work *done* in the past on light scattering techniques from complex random surfaces at large illuminating angles. At such angles Beckman scattering theory breaks down. The successful implementation of the SFD was a critical issue on the success of the QA system and the results proved that such **a** system is viable and effective.

2.1,4 Computer hardware

Textone and SFD are both imaging systems which require resources not ava!table in usual computer systems. At the start of the project extensive tests were performed on third party platforms. It was found that these could achieve only very basic functionality, and this at high cost, low reliability and without the ability to incorporate additional functions and devices necessary. The custom design of the hardware address all these issues is highly modular and can precisely target the processing power to the application.

The hardware of the QA system contains three components:
* an industrial PC c
• a microcontroller
s an image processing platform (IPP)

The industrial PC is the host computer. It is not involve in real-time processing and performs a supervisory role. It is provided with communications channels to other computers in the system and performs the functions of user interface, reporting system status, collecting system statistics, networking and diagnostics manager

The microcontroller controls all the real time events in the QA. station such as tra~king tiles, taking pictures, light level control, sorting mechanism, temperature control etc. [t is equipped with specialist controllers and interfaces to the QA system.

The IPP is a modular image processing computer that performs the image analysis required by the QA sta!ion. It is designed around a 19" rack which can accommodate various combinations of modules. This ability to target the hardware at the application is very important for managing the cost of the system while allowing for future expansion by adding more functionality.

The hardware uses an intelligent backplane which provides basic facilities common to all systems such as **a** pipeline control processor, image frame-stores, image bus crossbar switch with 17620 Mi-tz busses, and sockets for processing elements such as histogramrners, feature extraction, parallel processok, etc. These processing elements are able to perform specific functions at very high speeds using dedicated hardware.

2,1.5 **User interface and databases**
All interaction with the system is performed via a touch-screen-driven graphical user interface. This is managed, by the industrial PC. For the user in the tile factory this interface hides the system details and presents the sys!em in the context of the factory.

A great deal of effort has gone into the user interface design to make ii simple to use and guide the user through the various stages of machine operations in terms which reflect usual factory

operations. This has been designed in conjunction with quality control people in tile factories. This work has been extremely valuable in terms of the experience gained in how to marry the technology and its requirements to the needs and methods of tile production and quality control. Some typical screens of the user interface are shown below.
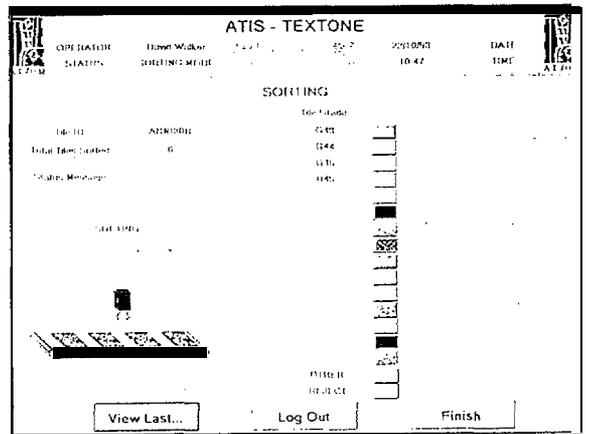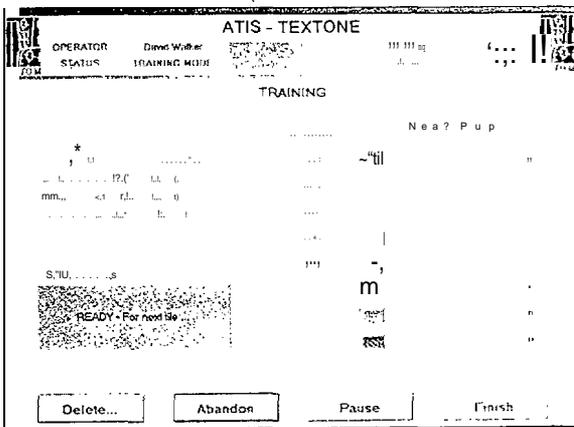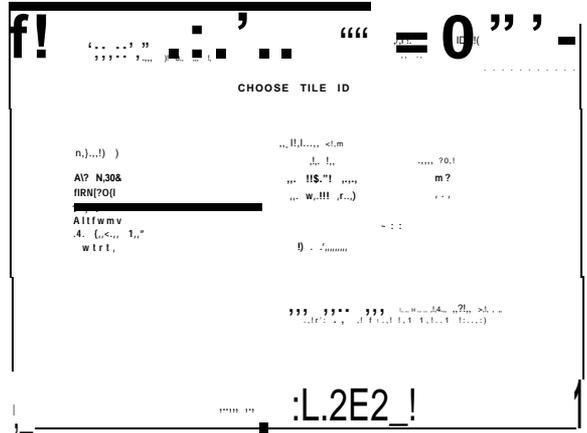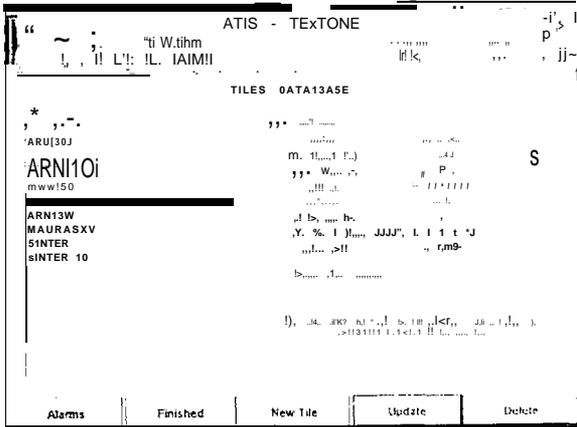
The user interface design incorporates the design of two separ'aje databases, one containing tile quality records and the other user information. The tile quality records are composed of tile information that can uniquely identify the particular model together with a description of the inspection environment prevailing during the initial training session when the quality record was first created. The intention is that the manufacturer can obtain the same results at any time in the future when it produces the same type of tile. The user interface was developed in English but an Italian version was also produced for Ihe live trials. The following operations are possible with the user interface:

- Teach the system how to grade tiles
- Instruct the system to sort tiles of a particular type
- Maintain a database of all (trained) manufactured products (tile qualitY records)
` Maintain a database of all sorted tiles (statistics, production size, grade variations etc)
- Monitor the state of the system, reporting and logging any abnormal conditions
- Maintain a users database providing security options
` Provide on-line help
` Proceed througl? an [nslallalion process and provide a health check of the system.

2.1.6. Planarity instrument

ArI additional component of the QA system is an instrument that measures flatness across the surface of the tile. This is also an optical instrument that works successfully at a resolution of near 0,1 mm with extremely good signal to noise ratio over a 30 cm width. The instrument can be deployed so that it uses only 70cm of production-line length.

This instrument is based on the principle of the Moire interferometer but using only one grid. The use of a single grid reduces instrument complexity and improves adaptability by allowing grid replacement without re-alignment.

The tile can be as much as 170 mm from the plane of the optics, unlike conventional moire systems which need to be very close to the object, thus allowing the optics to be separated from the dusty environment in a sealed enclosure.

No parts of the mechanical design are particularly critical. The grid must be held accurately but it is only about 30X3mm which is a convenient size and the geometry of the optics is quite compact and relatively easy,to produce. In addition the instrumen! has a Jarge depth of field thus reducing required system accuracies.

The theory has been tested successfully on the current prototype. Some further work needs to be done on the camera and illumination optics to obtain the best performance at cheapest cost.

2.2   In-process monitoring and control system

2.2.1 General

The development of process morlforing and control sensors and techniques met with some difficulties. Currently, ceramic tile production lines operate as a series of independent processes acting in isolation, In addition there is a total lack of interface uniformity between process machinery, and interfaces are proprietary and closed systems. These difficulties were overcome by designing a much more sophisticated system than originally envisaged and this development added time overheads.

A major step forward in lhe production process is to provide an integrated process monitoring and control system that can monitor and control all stages in the production process, viewing' the production as a whole rather than each step in isolation. Such a system, operating with a number of closed feedba~k loops has the ability to continuously modify the process parame,t'ers according to sensory inputs in order to achieve a level of product consistence currently unattainable.

The process and product monitoring system has been designed with a uniform two-level structure that allows any process or sensor to be incorporated in the system in an efficient and reliable manner. Each similar process is grouped together and each group is controlled locally by a group controller. In order to achieve this flexible architecture, process controllers, ~ group controllers and field bus interface adapters responsible for providing all group machines with a common interface regardless of their make, had to be developed.

A more serious difficulty for implementing process-parameter control was the fact that the diffErent production stages are completed at different rates and to compensate for the non-uniform rates extensive buffering is utilised with large scale intermediate storage. This type of production method makes it impossible to either track continuously a particular product or

close the control loop since by the time a product is being sorted some of the production phases have already been completed.

Th,e above difficulties meant that the design of the control system had to be implemented as a simulation running in a model factory.

2.2.2 Architecture

The design for the process monitoring system is shown in figure 2.1 below. Each similar process is grouped together and each group is controlled locally by a group controller.
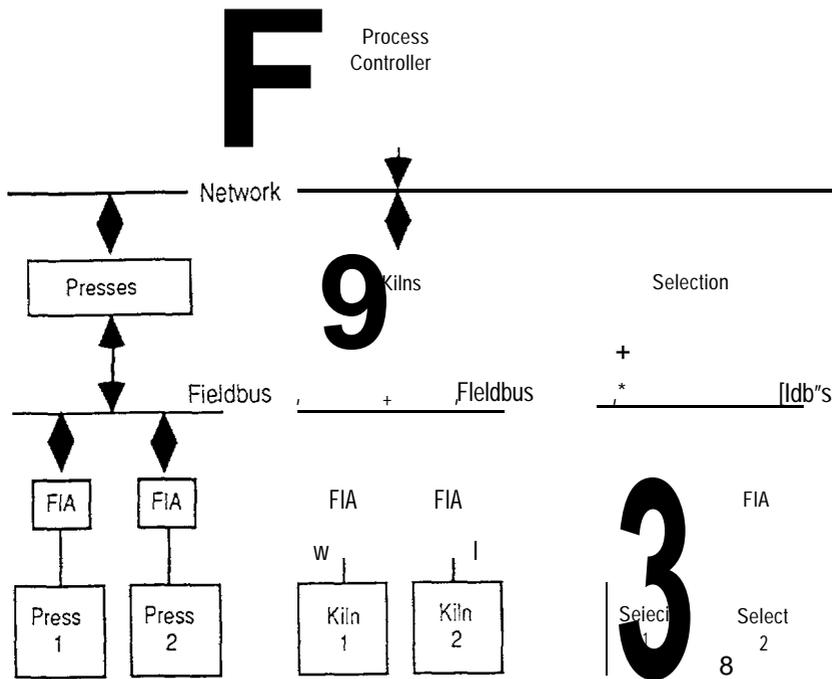

Figure 2.1   Process monitoring and control system

Process controller
The process controller is responsible for performing the process monitoring and control function, and it can access the various group controllers via a factory area network. The process 'controller can view the individual processes through the group controllers, and has a general model of each of the processes, i.e. it has one model of the kilns, one model of the presses etc.

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The group controllers are local to the group of ,Drocesses they control. They interface to the presses using a fieldbus connection to the Fieldbus Interface A6apter (FIA) which is located on the process machinery. The interface presented to the field bus by the FIA is the same for all process in the group. The process group controller localises process communication traffic on the fieldbus thus containing local traffic and reducing the load on the factory network. This approach has two benefits:

●Lowers bandwidth requirement for the factory network
●Facilitates physical interconnectioti of the processes.

Fieldbus Interface adaptes

The fieldbus interface ad~pters typically consist of a microcontroller with two interfaces. The FIAs are responsible for providing uniformity of control. The interface to the process group controller is standard for that process group; ali selection group FIAs appear identical to the selection group process controller, all kiln group FIAs appear identical to the kiln group controller etc. The other FIA interface, to the process machinery, is unique to that piece of machinery from that particular manufacturer.

The microcontroller provides the translation between the uniform interface and process specific interface, The FIAs are responsible for providing all processes with a common interface, regardless of the interface the manufacturer has provided. Ultimately, it is possible that all manufacturers will provided the common FIA interface as standard on their machinery although this would require an unusual degree of collaboration.

2.2.3 Implementation

At present, a continuous, closed loop feedback control system is difficult to implement because:

+ Factories use large scale intermediate storage in order to buffer the diverse production rates of sequential production stages.
.An initial investment is required to obtain a set of FIAs in order to get the system up and running.

The above difficulties have meant that the design of the closed loop feedback was implemented as a simulation on a model factory.

The design has been implemented as a Windows'M based user interface that displays a schematic of the plant. Each machine "is represented in a colour that indicates its status, and the machine can be selected to get access to each parameters.

The simulation approach w& useful for designing a factory installation as it allows models of the various processes to be created and the production process can then undergo initial tuning.

2,3   Computer aided design links

To aid the expert system in Ihe Quality Assurance system, a link from a CAD system, specifically modified for tiles, to the QA system was implemented. The CAD was developed on the Abode Illustrator. To implement the link from the CAD to the QA system, special modifications had to be made to the Abode's file format. The main addition is the provision for textural identifiers within Abode's annotation facility. All objects in the file with the same texture identifier belong to the same texture. The QA system may input extra meaning to any textural identifier, for example, in order to convey tolerance information.

The design data is passed to the user interface of the QA system and it allows the user 10 specify the design elements which share common surface characteristics, called textures. In addition, the computer based design system provides a priori information about each tile design to the vision system itself.

The vision representations required by the QA system are greyscale and black& white images of various filterings of the tiie design file. The filtered version can be colour, greyscale (e.g. for separations), or black & white (e.g. for masks), as required. Filtering takes the form of selecting which objects and which colours to include jn the output file. Thus all objects of a specific

texture or textures can be output as a mask or all objects of a specific colour or colours can be output as a separation.

A computer based design system has several advantages over conventional tools. (1) it allows the Q.A. system access to the design data, incorporating annotations provided by the designer specifically for quality control; (2) it allows separations to be produced automatically; and (3) it allows easier previewing. However, there are a number of constraints imposed on separations used for ceramics which are not resolved by currently avaiiable CAD systems:

- There is no direct correspondence between standard coiour code and ceramic ink colours
- Magenta and red inks are difficult to make for ceramics and are limited
- There are no standards for ceramic inks
- Colours can mix in unwanted or unpredictable ways during firing and therefore great care is required over which colours are allowed to overlap.

2.4. Mechanical transport and handling equipment

The development of new mechanical hand~ing and transport equipment was from the final C)A poinf to packaging and paltetising of the finished product ready for warehousing. The main areas of work concentrated on the development of special motors and drivers to achieve near absolute synchronisation of movement of parts without mechanical transmission. This not only achieves mechanical simplicity but also reduced wear.

The new mechanisms achieve higher operating speeds in terms of linear movement, an improvement of 600/0 average has been obtained, and an 80°/0 improvement in product handling accuracy. This aspect has benefits in reducing product damage during mechanical hand!ing and noise in the environment. To avoid increased transport speed causing damage to the tiles being stacked an extraction system has **been** desjgned based on rollers which enable the placement of tiles on to each other without scratching or impac!. This method of extraction has the added advantage of reduced noise during the stacking operations.

Production line speeds of up to 1 mls require packaging and palletising capability of nearly 9 to 10 boxes per minute. The packing machine boxes tiles using wrap-round cartdns or 'tray' cartons for bigger size tiles. Palletisation is performed by a robotic arm with a double size gripper, An SGV based orI laser 'beacons' and triangulation principle for position location and navigation has been implemented. The new palietising units and the SGV for automatic warehousing complete" the stages of rnecharrical **handling** and transport automation.

The stacking"tnechanism is ,shown in figure 2.2 and the robotic arm is shown in figure 2.3.

2.5 industrial trials

An integrated pilot system of mechanical handling and transport together with !he auiomatic inspection and quality assurance unit was installed in a tile factory in Italy where the existing factory-layout permitted full working trials.

The pilot has been tried for several months and a number of improvements discussed. The existing partners have decided to proceed with further development of the technology for commercial exploitation.
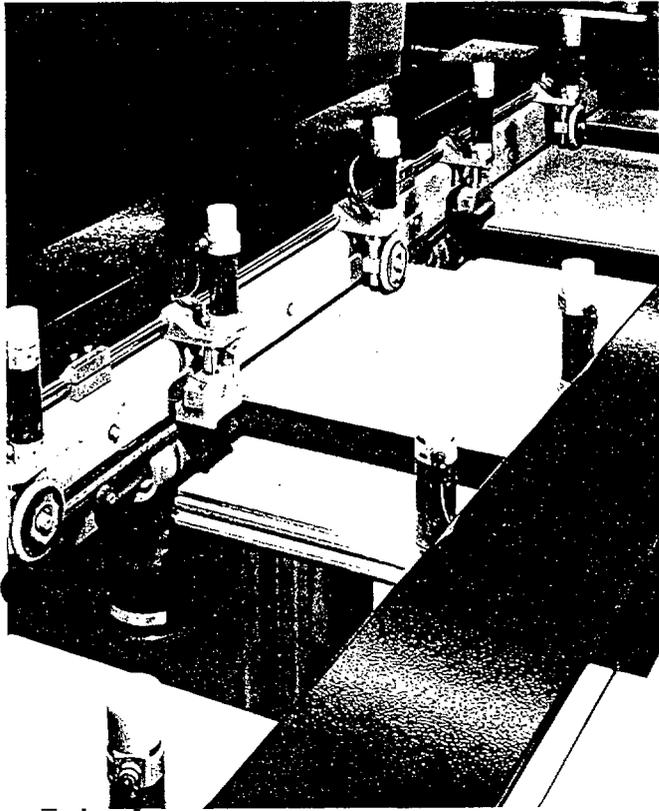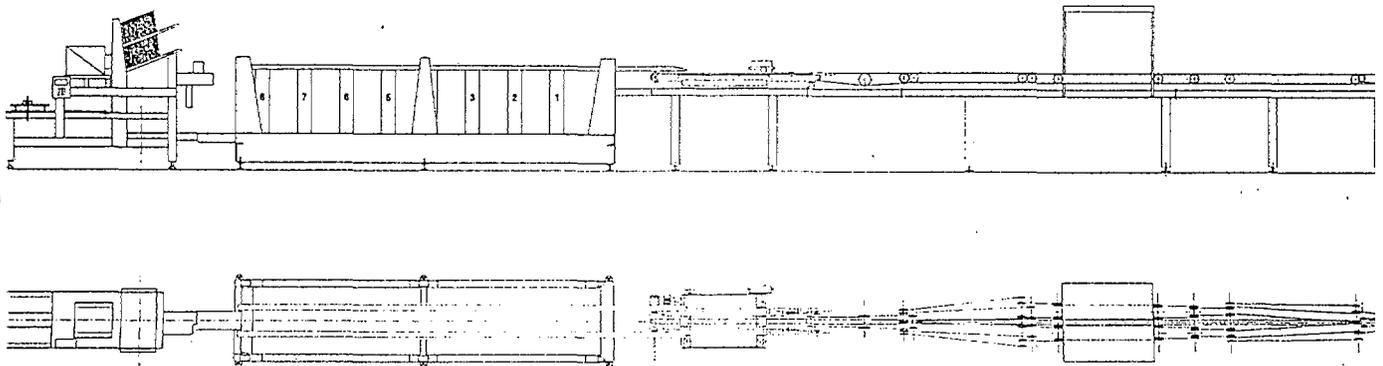
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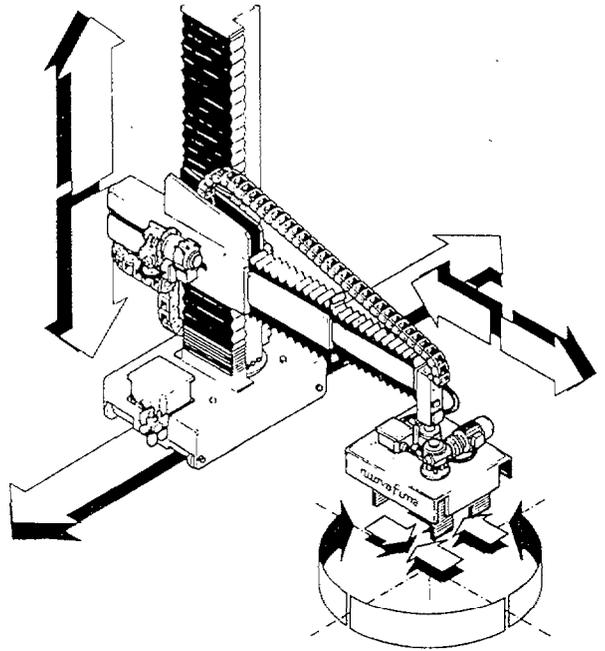
Palletising robot

Figure 2.2   Lay out of conveyor to QA system, stacking and carton packing

3 .   Concl usi ons

The original aims and innovations claimed by the project can be summarised in two broad statements:

- To provide a strafegic solution to shorten design-to-prototype cycle
- To develop the required technologies in order to enable in-process quality control at the critical stages of production.

Design-to-prototype cycle

The intention was to use a CAD system to shorten design-to-proiotype product cycle. By connecting CAD to vision, new designs can be obtained within minutes in a form that can directly be transferred to a printing device and under CAD control various designs can be produced in sequence, inspected and modified on the CAD system prior to their final adoption.

The result is a design-to-product cycle reduced from days to hours. [f implemented adequately, tile manufacturers could manufacture to-order at similar cost as long runs of producis. The price tag for the consumer would then be based on design and qua!ity of product in **a** similar way as the fashion industry.

The project has successfully completed the developments necessary to proceed with trials but there was not enough time nor the required facilities in terms of networking io proceed with production line trials. Over 800/0 of the original workprogramme was successfully concluded.

In-process quality control

The major part of the work planned was the development of a hybrid vision system that employed optics, special hardware and a-priori information derived from CAD. Its architecture was to meet the following criteria:- (1) iow cost, (2} high performance capable of full image analysis at production rates (1 m/s conveying speed) , (3} flexible configuration optimizing the use of computational modules.

In addition, **a user interface was required that allowed** teaching of features that might co-occur with flows, and user defined tolerances. It was to be adaptwe tn order 10 be able to set decision thresholds for assessing the extent to which desirable features , as defined by the tile manufacturer, co-occurred with flows for all types of tile products. "

CM successful completion of these aims a process control system was to be designed for the whole production of ceramic tiles.

All of the aims were successfully achieved. The degree of completeness of certain tasks undertaken varies between 800/0 and 100°/0, notably development and isolated trials were all completed 10OO/. but live trials, on real production lines were only achieved with some of the developments. The issues are explained in some detail in previous sections but the general reason was consistently the lack of available information and inadec,uate production environment facilities to enable such information to be obtained on-tree.

On the other hand the project achieved certain results which were not sl ated in the initial objectives and which have far reaching implications for the tile manufacturers:

- The need to establish objective quality standards. The system developed in this project enables, beyond original expectations, to establish such standards.

The work required will be time consuming and fairly tedious. 1[is not ciear whether it could be undertaken by any one of the partners.

- The need to develop coiour codes for the ceramic industry and appropriate CAD systems thus bringing ceramic CAD to the same level of ease of use as paper CAD.

  This is not a simple task because it would entail an expert system to map standard colour codes to resulting colours of fired ceramics.

- The urgent need to establish a complete monitoring system to enhance process k n o w l e d g e .

  The project has provided a complete, cost effective and easily implem en table solution. This achievement was not part of the original aims.

- The complete validation in ext~nsive live trial of a QA system, W-ich provides advar%ages not initially envisaged, su,ch as the ability to achieve multiple cat~gories of products in one pass and on-line, ability to adapt the selection process to custo~e[requirements without any time loss or added overheads, ability to obtain complele wcords of the production output.

To achieve the objectives the partners had to work very closely toge:her to a degree that was not thought originally necessary. The hospitality and support exwnded to the seconded members were unexpected and forged lasting relationships be;ween the collaborating organisations.

The consortium wishes to acknowledge the fact that without the help of the European Commission this project would have been impossible, National funds do not cater for translational collaborative projects and the aims of the projecl could not be achieved within the boundaries of any one member country only.