Automated Robotic Mass Production of Construction Will Limit Dangers to Human Operators and Achieve Maximum Production Efficiency

FutureHome: An Integrated Construction Automation Approach

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The FutureHome project [1] is a part of the Intelligent Manufacturing Systems (IMS) global program [2]. This program is an industry-led, international R&D program, established in 1995, to develop the next generation of manufacturing and processing technologies. Recognizing that these technologies will be expensive to produce, and that no single firm has all the expertise needed, companies and research institutions from Australia, Canada, the European Union (EU), Japan, Switzerland, and the United States have undertaken cooperative technology development to share costs, risks, and expertise. Over 250 companies and over 200 research institutions are currently active across an array of almost 20 active IMS projects.

Due to the fact that each geographical region funds its own IMS research, the same project has different names in different regions. This article deals with the first project in construction automation and robotics. The EU part of the project is called FutureHome, and the Japanese part is designated IF7. The FutureHome-IF7 project consortium is formed by leading construction companies and R&D centers from the United Kingdom, Spain, Germany, Finland, The Netherlands, Sweden, and Japan. This article presents the main results of the FutureHome project (1998-2001) in the area of modular house building, with an emphasis on the design and assembly stages.

The main objective of the FutureHome project is the development of an integrated construction automation (ICA) concept and associated technologies during all stages of the house-building construction process, from architect's desk to site robots, including

- modular design of buildings, keeping in mind their robotic erection
- automatic planning and realtime replanning of the offsite prefabrication, transportation, and onsite assembly
- onsite automatic and robotic transportation, manipulation, and assembly of the buildings' prefabricated parts.

Today, house-building methods are based on manual techniques that are slow, expensive, and noncoordinated. Each building continues to be unique in architecture and construction sense. Even though the investigation to develop new construction techniques has been important during the past years [3]-[5], there is still a long distance between the construction industry and other industries, such as the automobile industry. It is difficult to imagine houses being produced in the same manner as cars, but, at the same time, it is not possible to construct houses as was done 80 years ago [6].

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A change in construction methods and the acceptance of high-quality, flexible prefabrication technologies are essential for the construction industry. The challenge of this project is to automatically build different houses with the same prefabricated modules [7]. The benefits to construction industries can be improved by using advanced manufacturing systems. These modular systems will increase quality and customer satisfaction.

The idea of modular house building is not new. Several developments were attempted in the past [8], [9]. Some of them were applied in massive ways, in Eastern Europe, Germany, Japan, and other countries. However, all the past approaches did not solve three main problems

- quality of the modular houses
- flexibility in the design, i.e., different interior and exterior designs are made by the set of predefined modules
- robotic/automatic onsite assembly of modules.

The FutureHome project tries to avoid these disadvantages by introducing the ICA concept.

Modular Concept

The objective is to erect a building complex that consists of a set of buildings. Each building is erected using three-dimensional (3-D) modules and two-dimensional (2-D) panels (facades). These modules and panels are prefabricated offsite in a factory. Using beams, panels, installation elements, etc., 3-D modules are assembled in a flexible production line. Frames, panels, windows, doors, etc., are used to build the 2-D facade panels. Fig. 1 shows the tree structure of the modular building process.

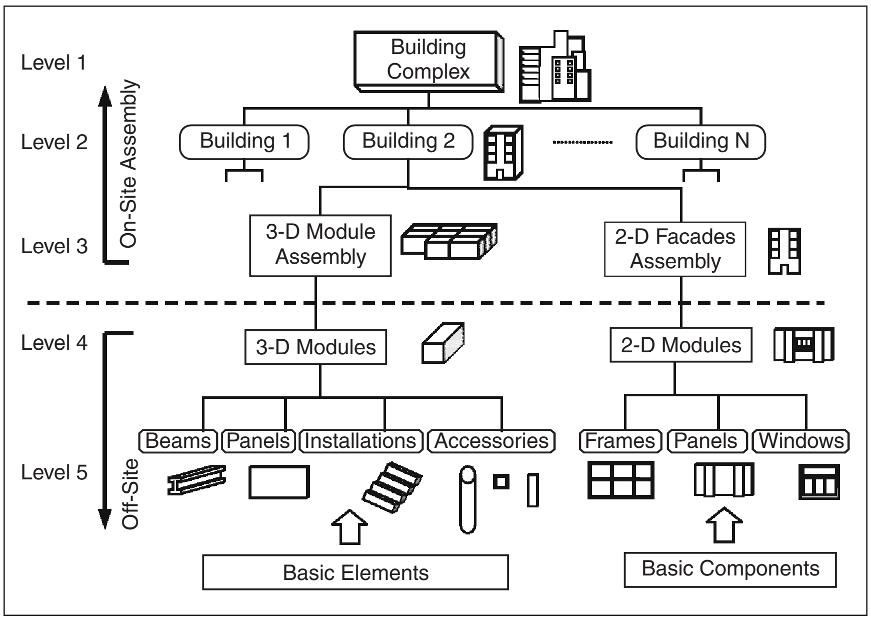


Figure 1. *Building complex tree.*

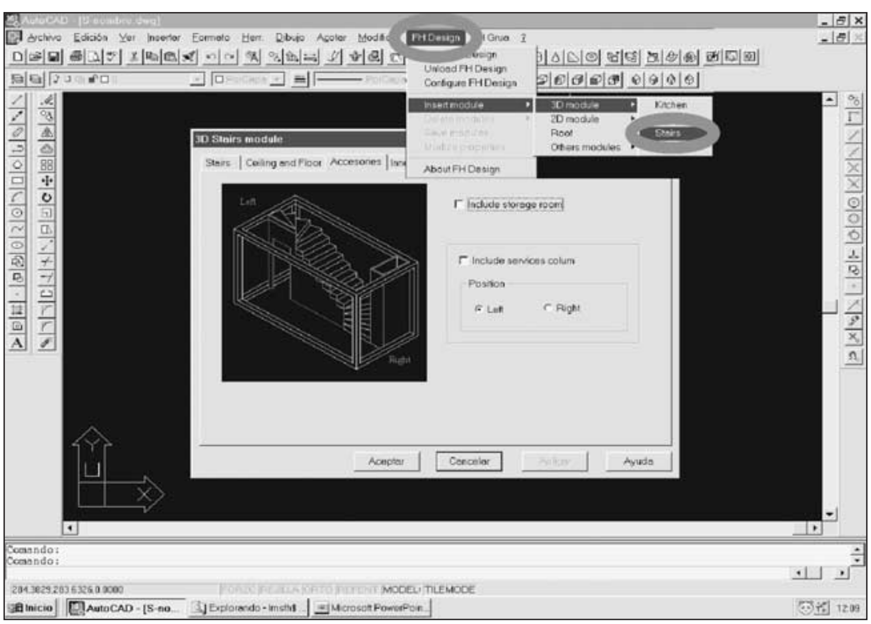


Figure 2. *Examples of CAD generation of the 3-D module (stairs).*

The architectural design implicitly carries the idea of singular buildings. This idea is not compatible with automatic mass production of modules. Making a group of different modules for each building may not be economically viable, but using an ample catalog of available modules should be sufficient to prevent the limitation of the designer's creativity. The solution should be a compromise between both ideas. The first step is the selection of the main module, with standard dimensions that can be adapted slightly, if necessary.

To define the 3-D modules' size, several features can be taken into account

- maximum dimension for factory manufacturing
- maximum dimensions for truck transportation
- maximum payload for onsite assembly machines, etc.

For example, in the FutureHome project for the end suites, closets, and bathrooms, the $2.4 \times 2.4 \times 3$ m ($l \times w \times h$ of external dimensions) size is selected, and for the staircase $2.4 \times 4.8 \times 3$ m is selected as a double module (Fig. 2). The 0.3-m grid is used for small modifications of the module.

Computer-aided design (CAD)-based modules can be manufactured in mass-production mode. An example of this technology is Japanese 3-D-modules manufacturing (Fig. 3). The modules are produced and equipped in factories, like cars in the automobile industry [10]. The modules include all external and internal elements, including electrical wiring, water pipes, etc.

One of the most important aspects of the developed modules is their ability to be automatically assembled. For this purpose, several assembly connectors were developed for the assembly of the modules themselves, the structural connection, and electrical and service pipes connections. These connectors permit automatic performance of complete assembly between modules. Fig. 4 shows the connector, which is able to accomplish the assembly of water pipes and/or wires [11].

Design Process

How will modern modular houses be automatically designed using the ICA concept? The process starts with the user's demand. Different users (a construction company, a real estate developer, or a final customer) have different needs: detached houses, semidetached houses, a row of terraced houses, apartment blocks, etc. Another important difference is the quality and type of materials employed in the construction, which are determined by the aesthetic preferences of the customer and economic factors.

According to customer specifications, the architect can design the building by two different methods (Fig. 5). The first method is based on a traditional architectural design that is commonly performed in 2-D. The architect designs the building without knowing that it will be constructed by modules. Then, this traditional design will be adapted to modular design using the specially developed AUTOMOD3 software package [12]. This package transforms the 2-D drawings into 3-D ones and automatically performs modularization of the building. The modularization can be divided in two parts: the calculation of the interior 3-D structure and the division of the external walls in 2-D panels [13].

During the modularization process, continuous adjustment of the modules' sizes has been performed using several criteria: maximum number of the same modules, maximum volume of the module, transportability of the modules, and many others. An example of this procedure is presented in Fig. 6, where different modularization criteria have been applied:

- Criteria 1: Modularization that takes into account the underground parking columns and vehicle circulation between them.
- Criteria 2: One module for one room.

Another important parameter taken into account during modularization is the structural calculation of the modules. The result of the modularization process is the list of modules which will be sent to the factory to be manufactured.

Figure 3. *Prefabrication of 3-D modules: (a) exterior and (b) interior views.*

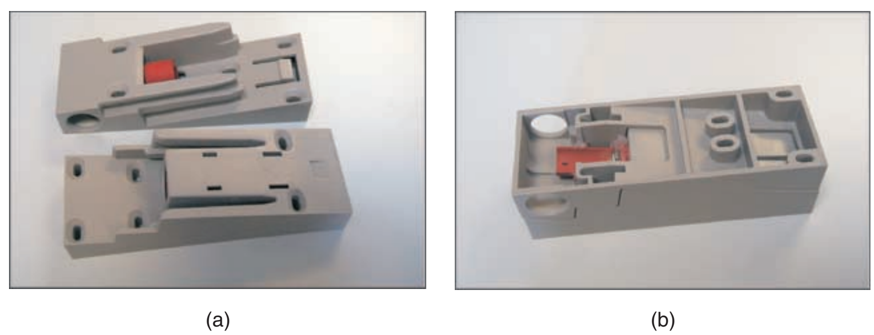


Figure 4. *Water pipes and wiring connector (a) disassembled and (b) assembled views.*

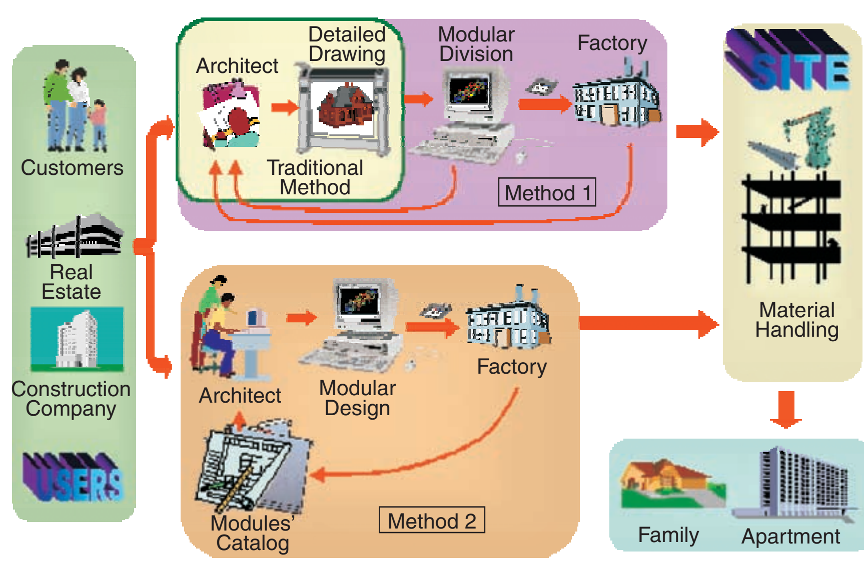


Figure 5. *Two methods of FutureHome design process.*

In the second design method (Fig. 5), the design is performed using a catalog of 2-D and 3-D modules. An architect selects the modules to design the building from a library. In this case, it is not necessary to calculate the modules; the list is directly obtained from the drawing. The modules' catalog is updated with new modules or modifications of existing ones. The factory provides information about modules, materials, accessories, and fabrication techniques that are employed to add new elements into the modules' library.

In this way, the building designed by traditional methods can be constructed by the modular system. Fig. 7 shows an example of this technology for an apartment building constructed in Torrejon de Ardoz, near Madrid. The drawings shown in Fig. 6 are part of this building.

The crucial point is the definition of the set of modules to be used. The geometry of the modules must permit the design of several different houses (exterior and interior) with a reduced set of modules. This idea leads to a compromise between the architect (responsible for the design stage) and the engineers (responsible for the prefabrication and onsite building-erection stages). For more variety of designs, more different modules are needed, and, for higher factory productivity of manufacturing modules, fewer different modules are needed.

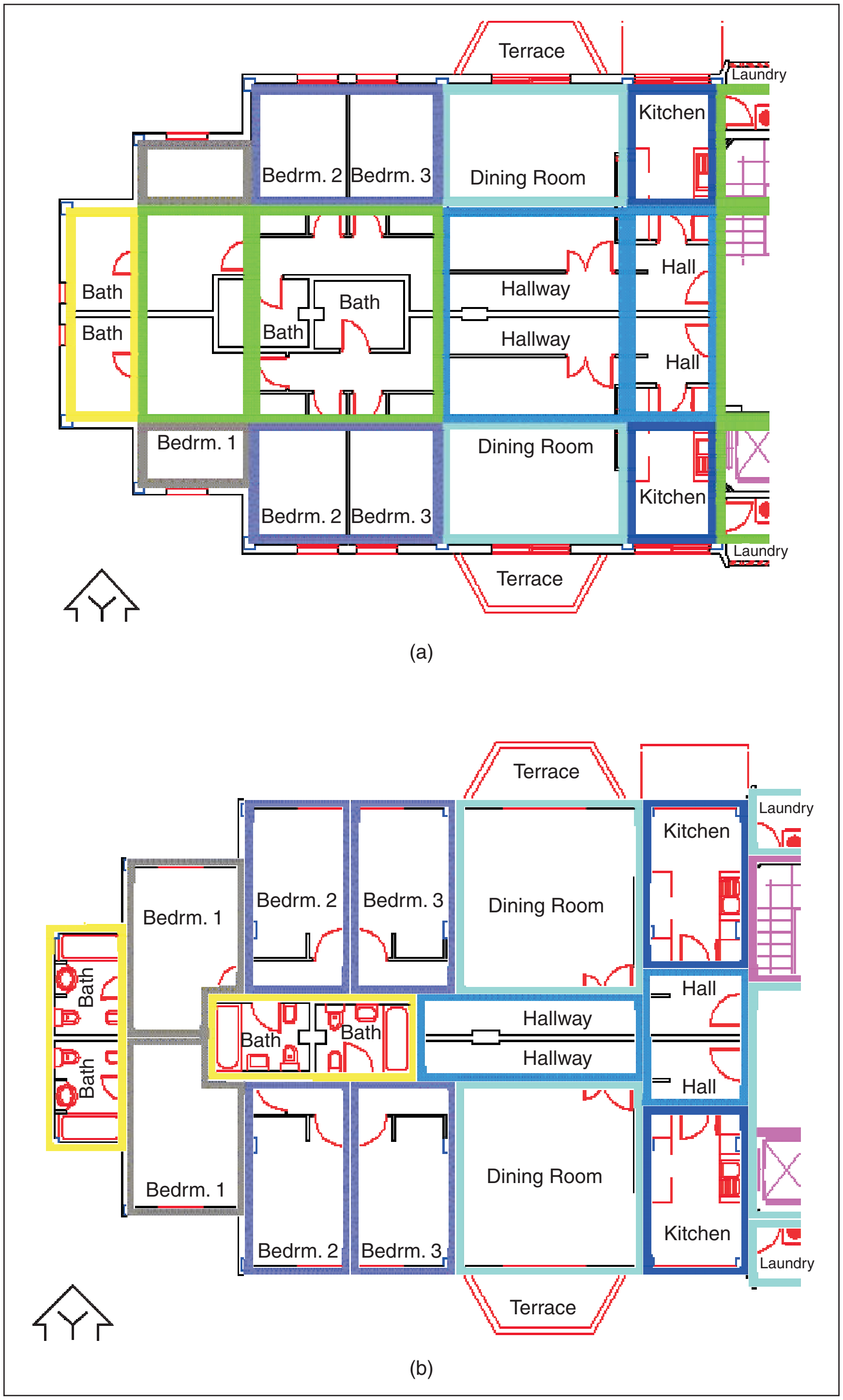


Figure 6. *Examples of modularization criteria: (a) Criteria 1 and (b) Criteria 2.*

As an example of this compromise, Fig. 8 presents four different designs that use only 20 different modules: seven different 3-D modules, eight different 2-D modules, and five different roof and chimney modules. The "Row of Houses 1" design uses 71% of the 3-D modules, 62.5% of the 2-D modules, and 100% of the roof-chimney modules. This means that the total percentage of modules used for this design is 75%. The "Row of Houses 2" design uses 80% of the modules, etc.

A specific tool for a general-purpose AutoCAD system has been developed to assist the architect in the design procedure described above. These process-oriented utilities are based on dialog boxes to guide the design process in an easy and friendly way. The designer follows the indications given in the dialog boxes to define the module's characteristics. Finally, the module is designed [14].

Planning Process

The planning process is an important part of the ICA concept. Its efficiency depends the productivity of the entire construction process. The planning process is represented in Fig. 9. It consists of three basic modules

- offsite factory planning for the prefabrication of the modules
- transportation planning
- onsite building construction planning, including the modules assembly.

In the construction of high-rise apartment or office buildings, a field factory is necessary. Its main mission is the onsite assembly of macromodules (big structures, blocks, etc.). In this case, the field factory is included in the planning process.

The planning process uses a layered architecture. Each layer plans the activities of each construction stage. The layers contain the planning procedures, the planning tools, the software applications, and specific formats for their exchange. The use of a layered architecture does not imply that the layered planning procedures are completely isolated. It may be necessary to establish global goals for the whole planning system. For example, in modular construction, it is necessary to decide what fabrication sequence is the most globally effective. In this way, it is necessary to calculate the optimum sequence

- for the whole offsite factory
- of transportation
- of the field factory
- of the onsite assembly processes.

Offsite and field factory planning is performed using the well-known computer integral manufacturing (CIM) concept [15]. Each factory plans and controls the output sequence of the fabricated modules, taking into account not only the time dependent manufacturing and transportation aspects (i.e., "just in time" or others), but also several aspects related to market, legal, and economic requirements. The relationships with suppliers are also very important parts of the planning process.

One of the most important layers is the onsite assembly planner. Onsite assembly processes are meant to be performed by robots and automated machines, like autonomous cranes, etc. In this case, the onsite planner is a four-dimensional (4-D) one, taking in account not only the geometrical constraints of the assembly, but also the time constraints. This layer determines the sequence in which different building components are assembled and plans the robot or crane trajectories for assembling them.

The developed tool is a visual editor running under the ObjectARX AutoCAD environment. This allows the integration of the planning subsystem with tools like ACIS, OSCON (architectural model) [16], and AutoCAD Architectural Desktop, among others. Communications can be ensured through the use of DXF files using IFC protocol. Fig. 10 shows an example of the planning procedure for the onsite assembly of "Row of Houses 1."

It is difficult to imagine houses being produced in the same manner as cars, but, at the same time, it is not possible to construct houses as was done 80 years ago.

The criteria for optimization of the onsite planner are very different and depend on the modules themselves, the layout of the site, the machines to be used, the number of these machines, etc. This is why the operator can select among the following planning criteria

- structure of the modules to be assembled
- levels or stories of the building
- distances between robots/cranes and modules (paths)
- the assembly process sequence

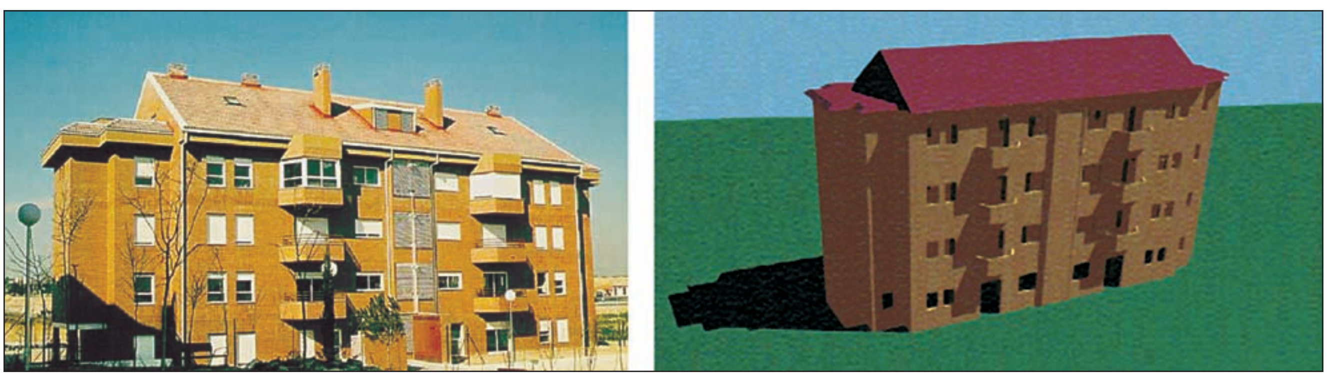


Figure 7. *Comparison of the real building and the CAD modular design building.*

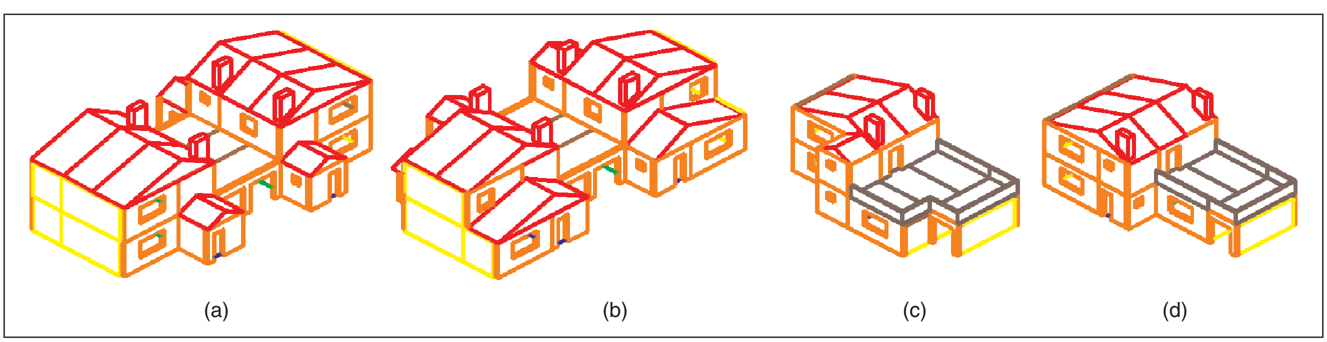


Figure 8. *Different designs of modular houses: (a) row of houses 1, (b) row of houses 2, (c) detached house 1, and (d) detached house 2.*

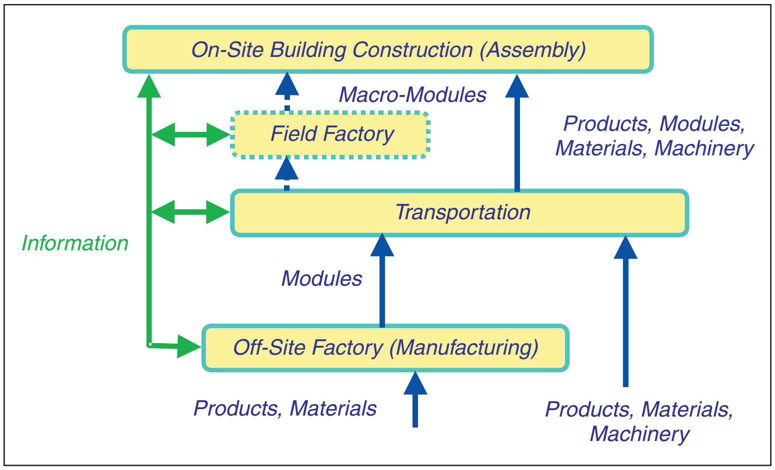


Figure 9. *Planning system layered architecture.*

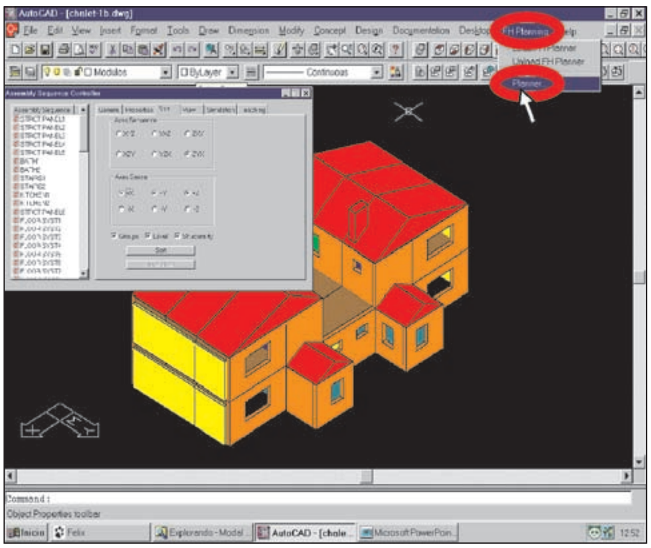


Figure 10. *Planner for the onsite process.*

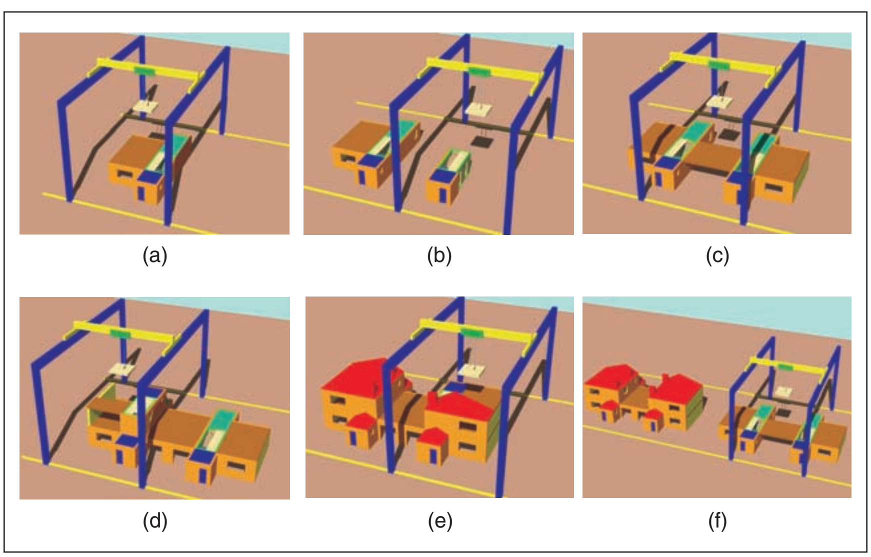


Figure 11. *Assembly sequence of the detached houses.*

- status of the modules "warehouse" for the optimization of the onsite flow of material.

Fig. 11 shows a sequence of semidetached houses assembled by an autonomous gantry crane. The building erection starts with the ground floor assembly of the left house (a), where the crane is in the left position. Then, construction continues with the ground floor of the right house (b), where the crane is in the right position. The common panels to both houses are assembled (c) with the crane in the central position. The next step is the assembly of the modules that form the first floor and the roof for left house (d), then, the right house (e). Finally, the next set of houses are started (f). In this way, the module sequence is decided as well as the crane's path.

Onsite Robotization

Manipulation and assembly procedures in the construction industry are totally different from other traditional industrial sectors, such as automobile manufacturing, electronics, etc. Industrial robots have a limited working area (some meters) and their payload is normally not very high (some tens of kilograms). This leads to high-speed and very high-positioning repetitivity (tenths of millimeters) of industrial robots. Robots in the construction industry must have totally opposite features: very big working area (tens and even hundreds of meters), very big payload (hundreds of kilograms or even tons), and it is not necessary to have very big positioning repetitivity (some centimeters).

During the last couple of years, some robots of this type have been developed. The most relevant examples are the ROCCO [17] and BLR [18] robots for brick assembly. These robots were specifically developed for masonry tasks and look like mobile cranes (range of 12 m). They are hydraulically driven, and their maximum payload is 300 kg. However, for the assembly of big 3-D FutureHome modules, this range and payload are not enough. For this purpose, other alternatives were looked into during the last couple of years. The idea is to use conventional construction machinery, like tower and gantry cranes, and transform them into robotic devices. Some examples of these types of robots are [19] and [20]. Nevertheless, their features and control strategies were not sufficient for the precise and quick assembly of FutureHome modules.

For the manipulation of heavy 3-D FutureHome modules (some tons) and their onsite assembly with small positioning tolerances (some centimeters), the most adequate crane is the gantry. It has very good mechanical rigidity and sufficient speed. Nevertheless, the steel cable transmission in the vertical (z) axis is a very big disadvantage, which creates swinging of the load (module). This drawback must be solved by an adequate control strategy, which will be discussed later.

The main idea is to use a low-cost commercially available gantry crane and transform it into a robotized crane by introducing the following modifications

- ac brushless servomotors in all axes (Baldor)
- vector control drivers for all motors (Baldor)
- position sensors (resolvers)
- a PC control system based on the multiaxis control board PMAC (Delta Tau).

In this way, the gantry crane is transformed into a three-degree-of-freedom (DOF) robotic system. For lab tests, the 1:3 scale system and modules were developed (Fig. 12). The movements in the x and z axes (trolley movement and elevation) are controlled by one motor each, but in the y axis (bridge movement), two motors are necessary: Y_1 and Y_2. Each of these two motors has its own control loop. To obtain the rectilinear movement of the y axis, the synchronization of the Y_1 and Y_2 axes is performed by a hierarchical master-slave strategy: the Y_1 is the master reference and Y_2 is the slave follower. This strategy guarantees the nonmisalignment of the gantry's bridge.

The hardware architecture of the system is presented in Fig. 13. The data from the design and planning PC is transmitted to the robotized crane's control PC. Each ac motor is controlled by its driver and resolver through the multiaxis board. The system is equipped with two types of sensors for the assembly procedure: two cameras and one 2-D inclinometer. The use of these sensors will be discussed in the next section.

The software architecture is formed by different software modules used in the control and the monitoring modes. The main program calls the modules in a synchronized manner using priorities and semaphores. In the case of the multiaxis control board, communication is performed in the form of character strings with special meaning to the card. These commands are calculated through a control algorithm to avoid undesired swinging of the load and taking into account the sensorial information of the whole system. Among the different modules, the graphical user interface (GUI) represents the main interaction gate between the operator and the robotized crane. It allows teleoperation of the crane as well as the execution of programs in a fully auto-

Figure 12. *FutureHome robotized crane.*

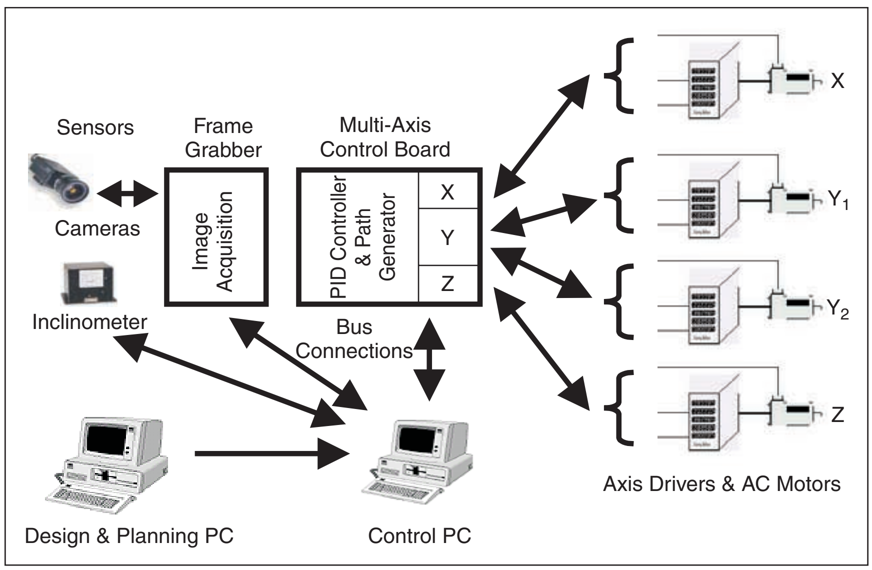


Figure 13. *Control system architecture.*

Figure 14. *Two methods of modules assembly: (a) manual traditional and (b) automatic.*

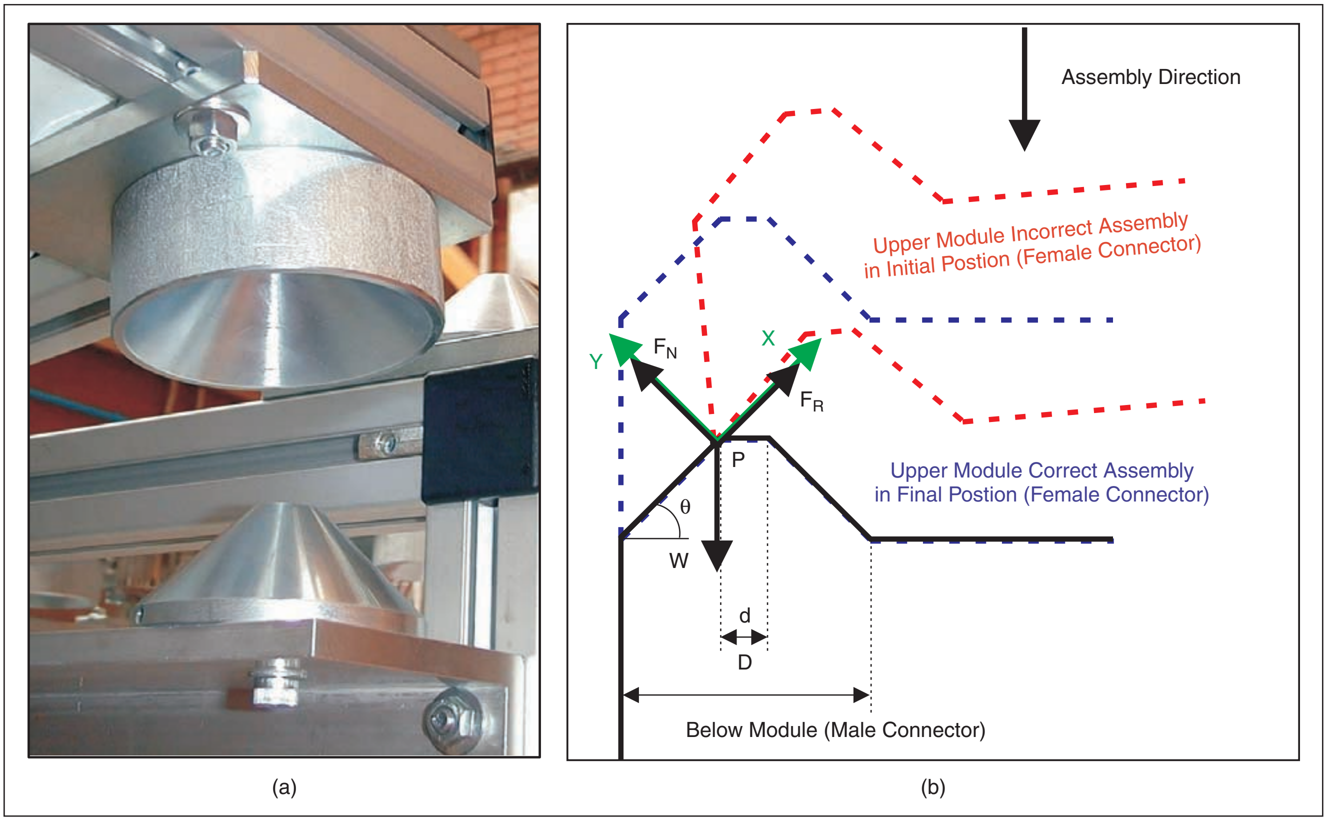


Figure 15. *Assembly connectors: (a) female and male connectors and (b) force analysis during the assembly.*

matic mode. The programming module is meant to allow the user to write and load existing programs from project databases. Sequences of module assembly generated by the planning tools, mentioned in previous sections, can be loaded from the database of a given project and interpreted to the crane programming language.

Modules Assembly Process

The correct positioning and assembly of modules is one of the most critical processes during the erection of a building. Normally, this operation is performed manually with several disadvantages: considerable danger for human operators, a high number of involved operators, and low productivity [Fig. 14(a)]. The automatic assembly of a module by robotized cranes is very convenient and avoids the above mentioned drawbacks [Fig. 14 (b)]. Nevertheless, for correct automatic assembly of big and heavy modules, the following elements must be introduced

- assembly connectors
- grasping mechanisms
- sensorial system integration
- antiswing control strategy.

Due to the fact that assembly is performed by the robotized crane in a vertical direction, the assembly connectors must compensate for positioning errors in the horizontal direction. Cones are a very good solution for the big positioning errors and permit autocentering of the module during assembly. The proposed geometry of these connectors are male and female cones. Each FutureHome module is equipped with assembly connectors in each corner of the floor (female cones) and of the top corners (male cones) [Fig. 15(a)]. The use of a connector in each corner can eliminate errors in all axes: horizontal errors, rotation error in the z axis, and module swinging. For big (double) modules, extra connectors are introduced in the middle. This type of connector allows a high tolerance, about 4 cm., of sliding the female part through the male one.

For correct sliding of connectors, force analysis during assembly must be performed [Fig. 15(b)]. The analysis is based on the force decomposition in the contact point *P*. Fig 15(b) presents the bottom positioning module (in black) with male connectors, the upper module correctly assembled in its final

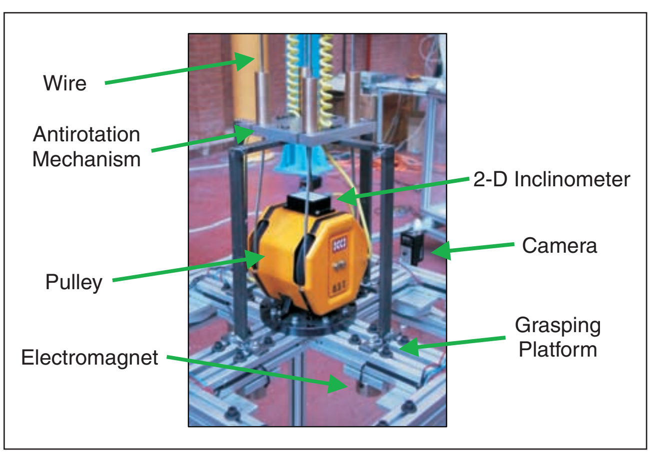


Figure 16. *The grasping platform.*

position (in blue) with female connectors, and the upper module during the first contact in point *P* (in red) with female connectors. Note that the last mentioned module has a misalignment in all the axes with respect to the bottom module.

The geometry of the cone is defined by the following parameters: base diameter *D*, top diameter *d*, the angle of the cone , and the height of the cone. The coordinate system of force decomposition is referenced to the contact point. F_N and F_R are the normal and reaction sliding forces in the contact point. *W* is the weight of the upper module. The equations of the contact are very similar to the whole-and-peg insertion [21], [22] and are the following

$$\begin{aligned} \Sigma F &= ma \\ F_R &= \mu F_N \\ W_x &= mg\cos\theta \\ W_y &= mg\sin\theta \\ \Sigma F_x &= F_R - W_x \\ \Sigma F_y &= F_N - W_y . \end{aligned} \tag{1}$$

Assuming that the upper female cone slides through the bellow male cone with a constant velocity, the acceleration *a* is zero, and ΣF=0. This fact leads to the conclusion that μ=tag θ, i.e., the friction coefficient only depends on the cone angle. At the same time, the friction coefficient only depends on the materials of both sliding parts. If these materials are lead and steel, μ=1 and the sliding force is F_R=693 N (for the 1:3 scale modules). If the materials are soft steel and soft steel, μ=0.57 and the sliding force is F_R=487 N. This leads to the conclusion that it is possible to use soft steel for both cones and, at the same time, select the cone angle of θ=45º to over-dimension the connectors.

The other cone parameters are: *D*=100 mm, *d*=20 mm, and *h*=40 mm.This geometry in four corners permits assembly correction without jamming and wedging, with a horizontal positioning tolerance of 4 cm, and with the misalignment more than 20º. Finally, the stress and strain finite elements analysis of cones confirm the goodness of the design.

Nevertheless, in the previous analysis, the important problem of flexibility of the four elevation wires was not taken into account. The steel wire is formed by several rolled thin wires. This fact makes the module's grasping element (platform) rotate in the z axis. To eliminate this rotation, a special grasping platform was developed (Fig. 16). The rotation is avoided by the special antirotation mechanism that guides the wires and eliminates the internal wires rotation tension, produced mostly in the pulleys area. The platform is also equipped with the electromagnets and female connectors to grasp modules.

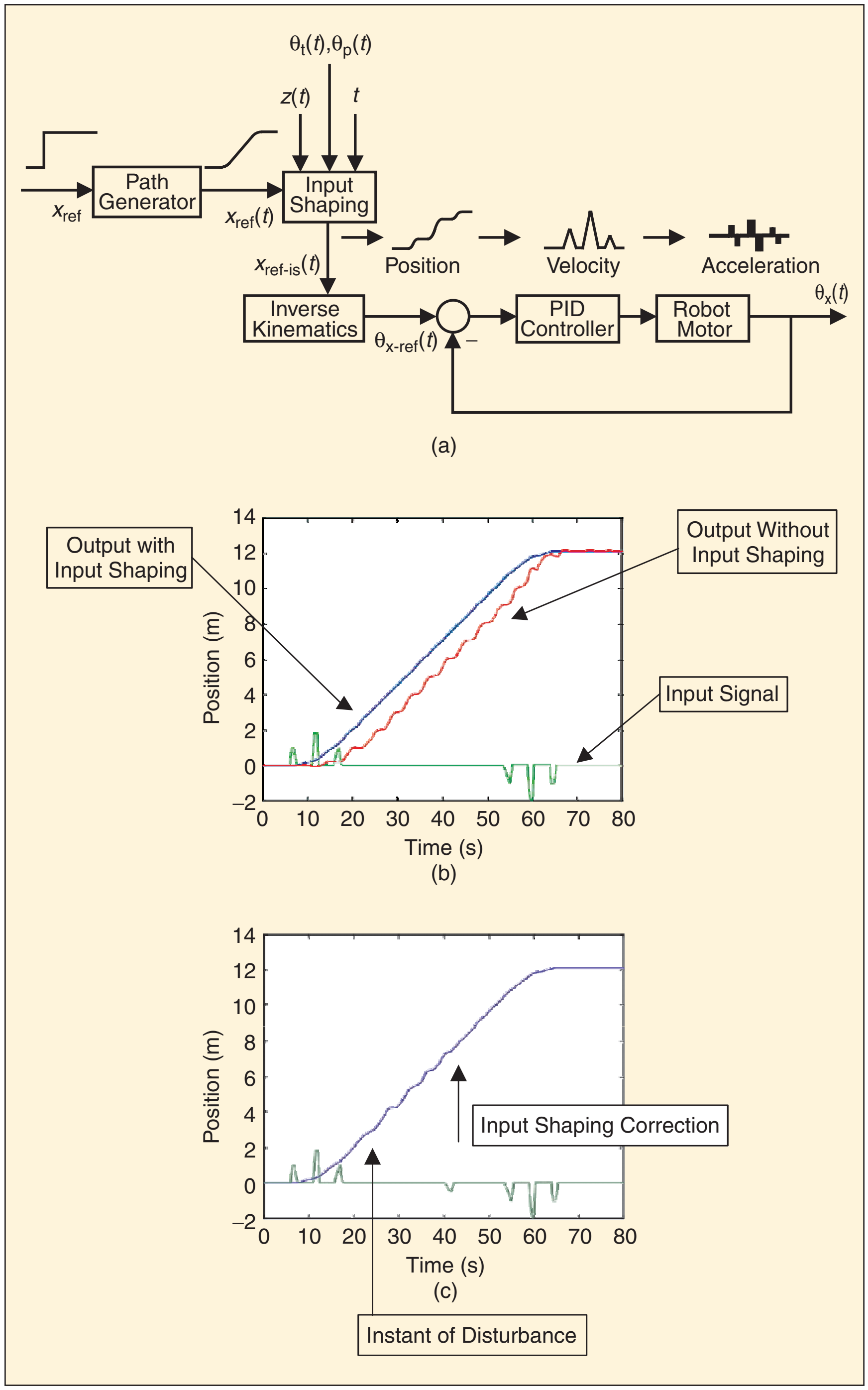


Figure 17. Input shaping control strategy: (a) control scheme, (b) experimental input and output signals (without disturbances), and (c) experimental input and output signals (with wind disturbance).

As described above, module assembly is possible with a horizontal positioning error of about 4 cm. If this error is bigger, correct assembly is impossible. To position the platform with the necessary positioning accuracy, several sensors are introduced in the platform. The sensors used are several cameras and a 2-D inclinometer. Normally the platform has two cameras. They are situated in the opposite corners of the platform. The cameras capture the images of the male cones of the bottom module with the top view. Then, the vision system calculates the cones' position with respect to the center of the platform. For this calculation *hue* and *saturation* transformations are used. Once the error between the desired and actual platform position is obtained, the robotized crane corrects its x and y position. This process is performed iteratively until the platform (with or without the module) is correctly situated. For big (double) modules, extra cameras in the middle of the platform are used.

Another important aspect to consider in order to perform the correct assembly is the swinging of the platform with or without a load (module). The special control strategy has been developed to avoid the swinging of the platform. The control is divided into parts: *Input Shaping* basic control [23] and modification of *Input Shaping* control by external inclinometer measurements. *Input Shaping* considers the platform and the steel wires as a pendulum. The oscillation of this pendulum depends on the known platform mass distribution and known wires length. Using these data, the theoretical period of this oscillation is computed. Considering that, in the initial position, the platform does not oscillate, the impulse commands (acceleration) are generated to move the x and y axes. The magnitude and the instant of the impulses are calculated to compensate the swinging in the moment of its maximum amplitude during the oscillation. Normally the sequence of two or three impulses is sufficient [24].

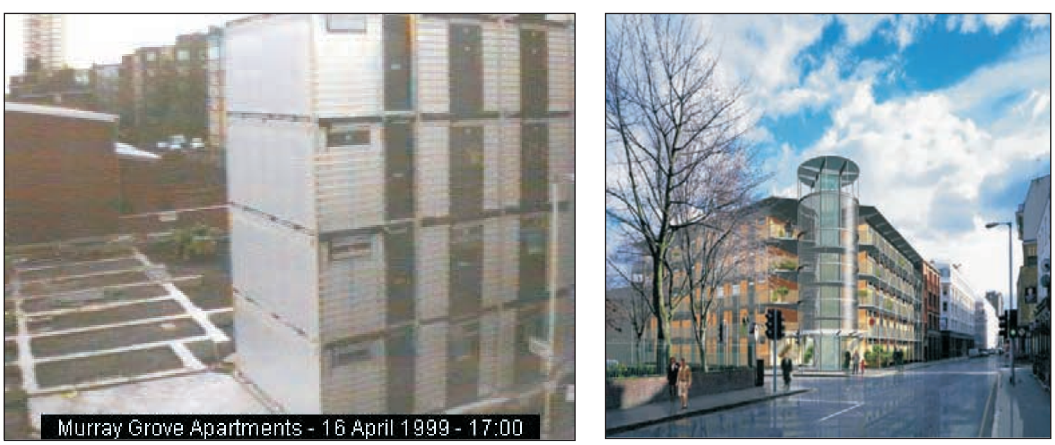
Fig. 17(a) shows the *Input Shaping* control strategy. The x_{ref} command is the desired reference position of the x axis (the same is done for the y axis). This command is transformed in smooth path $x_{ref}(t)$ by the *path generator*. Normally this signal is the input for the *inverse kinematics* module, which generates the angular reference for x axis $_{x\text{-ref}}(t)$. Using the *Input Shaping* control strategy, this angular reference is modified, taking into account the time t (directly related with the period of oscillation) and the position of z axis $z(t)$ (the length of the wire). In this way the desired step input reference of the x axis is transformed by convolution into smooth inputs which produce the platform movement without swinging. The experimental results of the basic control are presented in Fig. 17(b).

Nevertheless, the control strategy described above works in an ideal environment. If some type of disturbances (wind, asymmetrical distribution of the mass, friction, etc.) occurs, the system needs some external information about the swinging of the load (platform). For this purpose, a 2-D inclinometer is used. It provides the tilt $\theta_t(t)$ and the roll $\theta_p(t)$ angles with a sufficient sampling rate to identify the oscillation. This data is superimposed on the theoretical sequence of impulses generated by the basic control strategy. The experimental results with the wind disturbance are presented in Fig. 17(c).

Conclusion

This article presents the results of the FutureHome project, the first global project in the construction industry that introduces the ICA concept. The design, planning, and onsite robotization stages of house-building construction have been presented. The main advantage introduced by FutureHome is the integration of the three stages under common data and concept.

The article is focused in the architectural design of residential houses and office buildings by using prefabricated modules. The design takes into account the prefabrication and onsite assembly. For efficient construction, a global planning strategy has been developed that integrates the prefabrication, transportation, and onsite processes. Finally, the robotized crane for the assembly of big 3-D modules with small toler-



(a) (b)

Figure 18. *Murray Grove apartments in London (UK), 2000: (a) assembled modules and (b) complete building.*

ances is presented. The control strategy for adequate assembly with the reduction of positioning errors, rotation errors, and swinging of the modules, has been developed and tested.

Using part of this technology, an apartment building in London had been erected. Fig. 18(a) shows some assembly modules in the construction yard. Fig. 18(b) shows the finished building. Moreover, the new experimental residential building is actually under development in Ijmuiden (The Netherlands). This building will introduce most of the developed technologies and will be finished by the middle of 2002.

Acknowledgments

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Keywords

Robotics in construction, automatic house building design, planning, assembly

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