EU FutureHome Project Results

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ABSTRACT: The EU FutureHome project is focusing in the development of new modular building construction with several important features: high quality, variety of designs, mass production, reasonable cost, and etc. To reach this objective three main points can be study: a) integration approach during all the stages of the building design (from architectural design to civil engineering), b) standardization of the parts, the assembly technology, the joints, etc., and c) industrialization of the parts production. In this way, the main objective of the FutureHome project is the development of Integrated Construction Automation (ICA) concept and associated to them technologies during all the stages of the house-building construction process. This paper presents the main results of the EU FutureHome project focusing in the design, planning and on-site building erection processes.

KEYWORDS: Modular construction, integration, automatic design and planning, automatic assembly, robotized construction.

1. INTRODUCTION

The main objective of the EU FutureHome project is the development of Integrated Construction Automation (ICA) concept and associated to them technologies during all the stages of the house-building construction process [Balaguer 2002]:

- Design the buildings in modular way taking in mind their robotic erection.
- Automatic planning and real-time re-planning of the off-site pre-fabrication, transportation and on-site assembly
- On-site automatic and robotic transportation and assembly of the buildings' pre-fabricated parts.

Nowadays methods on house building are based on manual techniques that are slow, expensive and non-coordinated. 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 there is still a long distance between the construction industry and others industries, such as automobile industry. It is difficult to image houses being produced in the same manner as cars, but, at the same time, it is not possible to construct the houses as eighty years ago.

A change in the construction methods and the acceptance of the high quality and flexible prefabrication technologies are essential for the construction industry. The challenge of this project is to automatically build different houses with the same pre-fabricated modules [Balaguer 2000]. The benefits of construction industries can be improved by using advanced manufacturing systems. These modular systems will increase the quality and the customer satisfaction.

This idea of the modular house-building is not new. Several developments were done in the past [Naja], [van Gassel 1996]. Some of them were used in massive way in Eastern Europe, Germany, Japan and other countries. However, all the past approaches didn't solve three main problems: a) quality of the modular houses, b) flexibility in the design, i.e. different interior and exterior designs are made by the set of predefined modules, and c) robotic on-site assembly of modules. The EU FutureHome project tries to avoid these disadvantages introducing the ICA concept.

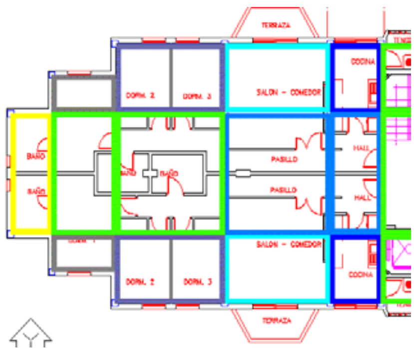
2. MODULAR CONCEPT

The objective is to erect a building complex that consists of a set of buildings. Each building is erected using 3D modules and 2D panels (facades). These modules and panels are pre-fabricated off-site in a factory. Using beams, panels, installations elements, etc., 3D modules are assembled in a flexible production line.

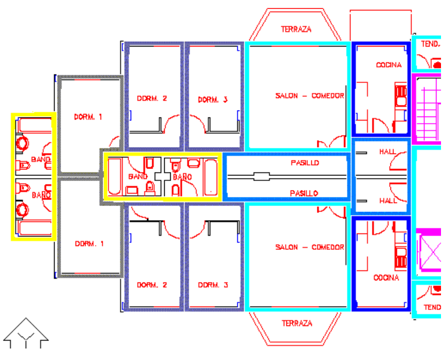
Frames, panels, windows, doors, etc., are used to build the 2D facade panels.
The architectural design carries implicitly the idea of singular buildings. This idea is not compatible with automatic mass production of modules. Making a reduced group of modules for each building may not be viable, but using ample catalogue of available modules should be sufficiently to prevent the limitation of the designer's creativity. The solution should be a commitment between both ideas. The first step is the selection of the main module with the standard dimensions which can be slightly adapted if necessary.
To define the 3D modules size several features can be taken in mind: a) maximum dimension for factory manufacturing, b) maximum dimensions for truck transportation, c) maximum payload for the on-site assembly machines, etc. As an example, in the FutureHome project for the en-suits, cloaks and bathrooms the 2.4 x 2.4 x 3 m (*l*x*w*x*h* of external dimensions) size is selected, and for the stair case 2.4 x 4.8 x 3 m is selected as a double module. The 0.3 m grid is used for small modifications of the module.
The CAD based designed modules can be manufactured in mass production way. An example of this technology is the Japanese 3D modules manufacturing. The modules are produced and equipped in factory like the cars in the automobile industry. The modules include all the external and internal elements, including power wiring, water pipes, etc.
One of the most important aspects of the developed modules is its possibility to be automatically assembled. For this purpose several assembly connectors were developed for: a) assembly modules itself, b) structural connection, c) electrical and d) service pipes connections [Bock]. These connector permits to perform in automatic way the complete assembly between modules.

3. 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 or a final customer) have different necessities: detached houses, semidetached houses, row of terraced houses, apartment blocks, etc. Other important difference is the quality and type of materials employed in the construction, which is conditioned by esthetical preferences of the customer and by economic factors.
According to the customer specifications the architect can design the building by two different methods. The first method is based on a traditional architectural design, which is commonly performed in 2D. 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 specially developed AUTOMOD software package [Diez]. This package transforms the 2D drawings into 3D ones and automatically performs modularization of the building. The modularization can be divided in two parts: the calculation of the interior 3D structure and the division of the external walls in 2D panels.
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.



a)



b)

Figure 1. Examples of modularization criteria: a) criteria 1, and b) criteria 2.

An example of this procedure is presented in the Fig. 1 where different modularization criteria have been applied: a) Criteria 1: modularization taking into accounts the underground parking columns

and vehicle circulation between them, and b) Criteria 2: one module for one room.
In the second design method, the design is performed using a catalogue of 2D and 3D modules. An architect selects the modules from a library to design the building. In this case, it is not necessary to calculate the modules; the list is directly obtained from the drawing. The modules' catalogue is updated with new modules or modifications of existing ones. The factory provides information about modules, materials, accessories and fabrication techniques, which is employed to add new elements into the modules' library.
The crucial point is the definition of the set of modules to be used. The geometry of the modules must permit to design a lot of different houses (exteriorly and interiorly) with the reduced set of modules. This idea leads to the compromise between architect (responsible of the design stage) and engineers (responsible of the pre-fabrication and on-site building erection stages). For more variety of designs more different modules are needed and for higher factory productivity of manufacturing modules less different modules are needed.
A specific tool for general purpose AutoCAD™ system has been developed to assist the architect in the above described design procedure. These process-oriented utilities are based on the dialogue boxes to guide the design process in an easy and friendly way. The designer follows the indications given in the dialogue boxes to define the module characteristics. Finally, the module is included into the drawing.

4. PLANNING PROCESS

The planning process is one of the important parts of the ICA concept. Its efficiency depends the productivity of the whole construction process. The planning process is consists of three basic modules: a) planning of the off-site factory for pre-fabrication of modules, b) planning of the transportation, and c) planning of the on-site building construction by assembly the modules. In construction of the high rise apartment or office houses field factory is necessary. Its main mission is the on-site assembly of macro-modules (big structures, blocks, etc.). In this case the field factory is includes 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 layers planning procedures are completely isolated. It can be necessary to establish global goals for the whole planning system. For example, in the case of modular construction it is necessary to decide what fabrication sequence is globally the most effective. In this way it is necessary to calculate: the optimum sequence for the whole off-site factory, the optimum sequence of the transportation, the optimum sequence of the field factory and of the on-site assembly processes.
The off-site and field factories planning are performed using well known CIM concept [Peñin]. Each factory plans and controls the output sequence of fabricated modules taking into account not only the time dependent manufacturing and transportation aspects (like, just in time or others) but also several aspects related to the market, legal and economical requirements. The relationship with the suppliers is also very important part of planning process.
One of the most important layers is the on-site assembly planner. The on-site assembly processes have been performed by robots and by automated machines, like autonomous cranes, etc. In this case the on-site planner is a 4D one, taking in account not only the geometrical constraints of assembly but also the time constraints. This layer determines the sequence in which different building components are assembled and it plans the robot or crane trajectories for assembling them.

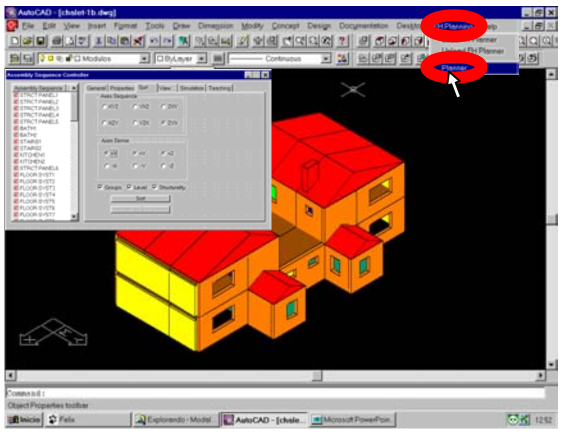


Figure 2. AUTOMOD3 lanner for the on-site processes.

The developed AUTOMOD3 tool is a visual editor running under ObjectARX™ AutoCAD™ environment. Fig. 2 shows an example of the planning procedure for the on-site assembly of "Row of houses" [Padron]. This tool allows the integration of the planning subsystem with tools like the ACIS™, OSCON™ (architectural model) [Trasey] and the AutoCAD™ Architectural Desktop, among others. The communications can be by DXF files of IFC protocol.

5. ON-SITE ROBOTIZATION

Manipulation and assembly procedures in construction industry are totally different from other sectors, such as traditional industrial sectors (automobile, electronics, etc.). Industrial robots has a limited working area (some meters) and its payload is normally not very high (some tens of kilos). This leads to high speed and very high positioning repetitivility (tenths of millimeters) of industrial robots. Robots in the construction industry must have totally opposite features: very big working area (tens and even hundreds meters), very big payload (hundreds of kilos and even tones) and it is not necessary to have very big positioning repetitivility (some centimeters).
During the last years some robots of this type have been developed. The most relevant examples are the ROCCO [Balaguer 1996] and the BLR [Heintze] robots for brick assembly. These robots were specifically developed for masonry tasks and looks like a mobile crane. They are hydraulically driven and its maximum payload is 300 kilos. But for the assembly of big 3D FutureHome modules this payload is not enough. For this purpose other alternative was checked during the last years. The idea is to use the conventional construction machinery, like tower and gantry cranes, and transform them into robotic devices. Some examples of this type of robots are [van Gassel 1993] and [Tomczyk]. Nevertheless, its features and its control strategy were not sufficient for the precise and fast assembly of FutureHome modules.
For the manipulation of the heavy 3D FutureHome modules (some tones) and for its on-site assembly with small positioning tolerance (about 5 centimeters), the most adequate crane is the gantry one. It has a very good mechanical rigidity and sufficient speed. Nevertheless the steel cable transmission in vertical (Z) axis is a very big disadvantage which create swinging of the load (module). This withdraw must be solved by adequate control strategy [Garrido].
The main idea is use a low cost commercially available gantry crane and then transforms them into robotic system by the following modifications:

- Introducing of the AC brushless servomotors in the entire axis.
- Introducing the vector control drivers for all motors.
- Introducing position sensors (resolvers).
- Introducing the PC control system based on the multi-axis control board.

In this way the gantry crane is transformed into 3 DOF robotic system. For Lab test the 1:3 scale system and modules are developed (Fig. 3). The movements in X and Z axes (trolley movement and elevation) are controlled by one motor each, but in the Y axis (bridge movement) it is necessary to motors: Y1 and Y2. These two motors have it own control loop. To obtain the rectilinear movement of Y axis the synchronization of Y1 and Y2 axes is performed by hierarchical master-salve strategy: the Y1 is the master reference and Y2 is the slave follower. This strategy guaranties the non misalignment of the gantry's bridge.

Figure 3. FutureHome robotic system.

The system is equipped with two types of sensors for assembly procedure: two cameras and one 2D inclinometer. 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 the priorities and semaphores. In the case of the multi-axis control board the communication is performed in 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 User

Graphical Interface represents the main interaction gate between the operator and the crane. It allows the Tele-operation of the crane as well as the execution of programs in a fully automatic mode. The programming module helps the user writing and loading 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.

6. MODULES ASSEMBLY PROCESS

The correct positioning and assembly of modules is one of the most critical processes during the building erection. Normally this operation is performed manually with several disadvantages: a) a big dangerous for human operators, b) a high number of involved operators, and c) a low productivity. The automatic assembly of module by robotized crane is very convenient and avoid the bellow mentioned withdraws. Nevertheless for correct automatic assembly of big and heavy modules the following elements must be introduced:

- Assembly connectors development
- Grasping mechanisms development
- Sensorial system integration
- Anti-swing and control strategy

Due the fact that assembly is performed by robotized crane in vertical direction, each FutureHome module is equipped with assembly connectors in each corner. The geometry of these connectors are male and female cones (Fig. 4). This type of connectors permits to perform the assembly process with a big tolerance, about 5 cm, sliding one female part through the male one.

For correct sliding of female connector through male one the force analysis during assembly may be performed. The analysis is based on the forces reactions. As a result of this analysis, the exact geometry and material are selected. Supposing that the modules cross section is 100 mm (laboratory size), then we choose the connector bottom base to be this size. For the angle size we have to reach an agreement. It has to have the adequate size for sliding and to avoid jamming and wedging. We come to the conclusion, by force decomposition, that μ = tag θ. Therefore, knowing that our scaled modules are made of Aluminum μ = 0.47, the connectors angle has to be at least 25º. To make things easier we choose a θ value of 45º.

Figure 4. FutureHome assembly connectors

7. CONCLUSIONS

The FutureHome project develop and introduce a new integrated concept for automatic modular construction using integrated approach. All the stages of the processes are integrated in the same programming environment and have coordinated communications.

As the demonstrator of the project, a real residential building was built in Ijmuiden (The Netherlands) by CORUS, one of the industrial partners of the project (Fig. 5 and 6). The building includes most of the developed technologies and concepts of the project. The used materials are mainly lightweight steel, aluminum, wood and plastics.

Figure 6.FutureHome prototype.

Figure 6. Interior view of the FutureHome prototype.

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