Automation And Integration Of The Design And Construction Of Concrete Buildings

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ABSTRACT

The study reported in this paper demonstrates an interactive Computer-Integrated Construction system (CIC) with graphic display for custom design of concrete buildings and automated on-site implementation by robotic devices. The developed system utilizes standardized reusable modular forms which are specially designed for assembly and disassembly by robots. These forms serve as the link between design and construction. An interesting feature of the system is the ability to use the design information to automatically generate optimized construction planning and scheduling information for any weighted function of cost and desired time for completion. The study represented is a simulation to investigate the feasibility of such integrated system.

1. INTRODUCTION

The remarkable progress of Computer-Integrated Manufacturing (CIM) and Automation in the manufacturing industry can be an excellent incentive to the construction industry to solve these problems[1]. Many successful CIM and Automation concepts such as the integration of the management, planning, design, and manufacturing operations can define goals to make better use of Automation and Robotics in the construction arena. Good progress has been made in the automation of some construction activities at the work site, which focuses on automating individual processes[2]. However, it is the integration and simplification of these activities, and approaching the problem from a total system viewpoint that is severely lacking in the construction industry.

The methodology introduced in this paper describes an interactive Computer-Integrated Construction system (CIC)[3] with graphic display for custom design of concrete buildings and automated on-site implementation by robotic devices. The developed system utilizes standardized reusable modular forms which are specially designed for assembly and disassembly by robots. These forms serve as the link between design and construction.

2. THE FRAMEWORK OF THE CIC METHODOLOGY

Figure 1, describes the framework of the developed Computer-Integrated Construction (CIC) system. The core of the CIC system is formed by a Microsoft Windows (i.e., menu-driven system) based application that allows the user to do the following:

- Create and load a 3D computer model of construction components for a project, into its data-base. Also, all the related information to both components and construction machines are incorporated within the data-base.
- Allow for easy modification within the construction model.
- Relate scheduled activities for optimum cost and time of construction.
- Gives complete instructions to the robotics system of when and how to assemble or disassemble construction components.
- Create a custom simulation of any portion of the construction project.

The CIC system is formed by a library of three systems from which a symbolic or a graphical project model can be established. These are: a design system, a process planning system, and a construction robotics execution system. All systems are linked through a common graphical component-based data-base which provide the paradigms necessary to achieve such a knowledge-rich representation of a construction project.

3. ACTIVITY-ORIENTED CIC DATA-BASE

A graphical activity-based data-base, within the CIC system, is developed. This data-base, primarily, captures the geometric information and the necessary features of the modular form system for construction project design and then uses this information to facilitate the automation of production planning and construction. The geometric description is only one piece of information or one element of the total table of functions about the construction project model. The construction project model is a computer representation of the construction project structure. It contains form geometric and non geometric attributes, connectivity, dependencies, production and cost constraints, and access to robotics hardware systems. Table 1 shows all types of data to be inputted and stored within the data-base. All these data can be retrieved interactively by the user through the program structure. Figure 2 displays a 3D model of a modular 4-Sided column form and its associated data or knowledge.

4. THE INTERACTIVE DESIGN PROCESS

The main objective of the design procedure, as part of the total construction realization system, is to achieve design-construction integration. This is accomplished through the CIC system as follows:

- Data representation standards that will permit the efficient and accurate transfer and sharing of data between the various construction systems procedures.

- The efficient representation of project components as object models linked to 3D CAD models.
- Interactive representation of data for design, implementation, and modification.

5. THE AUTOMATION AND OPTIMIZATION OF CONSTRUCTION PLANNING

An integrated construction planning system is designed within the CIC system to automatically transform the modular formwork construction design and implementation processes into a well-structured data representation (i.e., knowledge)[4]. These data can, then, be represented as graphical activity networks. This system lets the designer evaluate and modify the necessary activities, precedence, estimates duration's, and the required resources at any stage of the construction process. At the end of the design, the entire activity network can be assembled, displayed, and optimized after the acceptance of both the designer and the construction engineer. The goal of process planning is to allocate combinations of construction components and resources to every level or stage of the building project produced. The goal of production planning is to achieve the production of the different levels or stages within the design specifications, given time, and in the most economical way.

The developed system would allow the automatic evaluation of the graphical component-based representation of a construction project leading to the development of optimum production/process planning. Recent innovations in computer software technology in such areas as Knowledge-Based systems, Expert systems, and Object-Oriented programming have provided a useful mechanism to integrate, or organize, and structure construction design and planning information. They assist in rapid prototyping of software by providing tools for data encapsulation, narrowly defined data structure inferences, modular development, and class structuring[5].

5.1. KNOWLEDGE REPRESENTATION OF CONSTRUCTION PLANNING

Within the design and implementation processes of the CIC system, all activities are divided into discrete construction levels and stages, and most of these activities are dependent on their predecessors. Each construction activity of the building process describes the application of **Activity Generator** which is a set of computer commands incorporated within the CAPP system[3] that generates activity's knowledge (e.g., type of activity, location, time, and cost) and activity's precedence network.

Table 2 represents a sample of the **Activity Generator** and its knowledge for designing and implementing the process (e.g., at any level and stage) of placing any modular forms in their location. All other activities for the construction of the building can also be described, at any level and stage, by the application of these generators according to a specific CIC program structure design and implementation commands. Within the CIC program structure, if the designer starts designing and implementing a column form, the **Activity Generator** will simultaneously generate the equivalent commands to construct the column form. It will start initiating the (**Transport_Column Form[Level=1,Stage=13]**) command and the (**Place_Column Form[1,13]**) command to start the placing process of the selected form to its exact location using the type of robot selected by the designer. The designer can view these generated instructions or commands after each stage of the construction sequence. The designer can, then, select the menu [**"Generate"**] and the submenu [**"Process Planning Instructions"**] to view the process planning instructions generated automatically by CAPP through the **Activity Generator**. The designer has the option to view the default level and stage (i.e., current level and stage) or previous levels and stages of the building process planning. Figure 3 displays the automatically generated process planning instructions (or knowledge) for the design and the implementation of the column modular form.

The process planning instructions generated automatically by CAPP through the **Activity Generator** is also transformed into an activity network that is a graphical representation that simulates the Critical Path Method graphical techniques. The graphical representation of the activity network is the backbone of CAPP. Figure 4 and 5 display samples of the automatically generated activity network for the placement and removal of the vertical modular forms, respectively.

5.2. OPTIMIZATION OF CONSTRUCTION PLANNING

Once the designer has completed the preliminary design and implementation of the building project model, the CAPP system will generate a strategy to optimize the construction process planning according to the established output requirements of each level and stage. The objective of optimization of the construction planning can be formalize by the following general linear objective function:

$$U = C_{total} + k\left|1 - \frac{T_{total}}{T_{desired}}\right|$$

Where;

- C_{total} = The total cost calculated to finish of the building model. This cost includes the cost related to transporting, placing, and removing the modular form system and the cost related to the robotic devices.
- T_{total} = The total time calculated to finish all stages within all levels of the building model.
- $T_{desired}$ = The total time desired by the designer or the customer to finish all stages within all levels of the building model.
- k = A weighting factor that depends on the designer and customer optimization strategies.

The planner can automatically generate the activity network at any stage for inspection and modifications by the designer or the construction engineer. At the end of the design process the entire network can be displayed and optimized after the acceptance by the designer and the construction engineer. The optimization scheme can also be performed at different levels of the construction process, such as stage, event, level or the entire construction process that makes the integrated system a dynamic process. The CAPP system will automatically find where the *critical stages* (e.g., the stage that takes long time) and modify it by adding a parallel operation or rearrange the order of operations. The output measurements of this optimization scheme are the number of parallel construction operations and the best order of operations that will ensure minimum deviation from the target finish time with the lowest cost. The number of parallel construction operations will represent the maximum possible number of robots that can execute the parallel operations. The maximum number of robots that can be allocated to the parallel operations is constrained by the geometry of the construction location. Therefore, the number of robots that can be utilized to carry out parallel operations if needed to meet the target date is an important factor or constraint affecting the optimization process.

6. CONCLUSION

The CIC system described in this paper illustrates the feasibility of an integrated interactive system for automating the construction of custom designed concrete buildings. The design and construction activities can be planned, rehearsed, modified, optimized, and checked in a systematic interactive manner. The process of assembly and disassembly of the form is then documented as a full set of instructions to be used by on-site robotic devices. The necessary forms, robots, and end-effectors would be scheduled and handled *just in time* for use in the automated construction. The CIC data-base can provide at any stage a visual display of form geometry and connectivity requirements regarding the formwork components. This information is then interfaced with the implementation procedure to initiate planning and execution of the construction process.

The interactive computer system automatically transforms the modular formwork construction design and implementation processes into a well-structured data representation (i.e., knowledge) which can be displayed as graphical activity networks. It therefore allows the designer to evaluate and modify the necessary activities, their precedence, and the required resources at any stage of the construction planning process. At the end of the design and implementation processes within the CIC system, the entire activity network can automatically assembled, and displayed after acceptance by the designer, the construction engineer, and the client.

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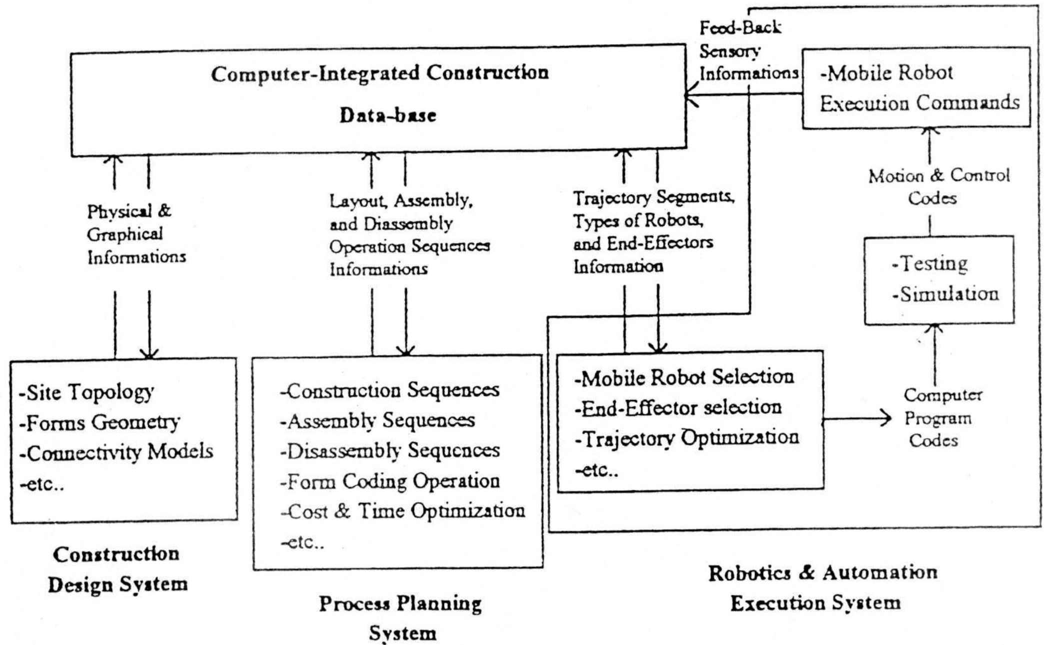
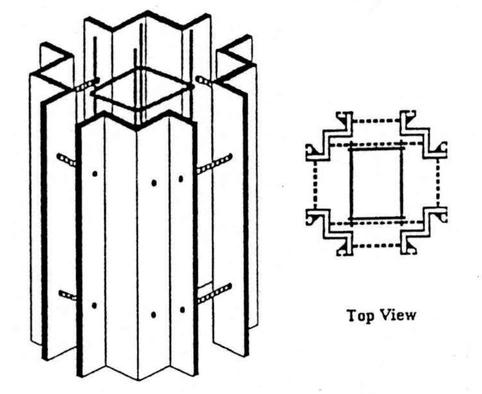


Figure 1 : Computer-Integrated Construction System Outline for the On-Site Robotics Construction System.

Type of Data	Hardware	Types of Hardware	Input Data	Stored Data
Design	Forms	-Vertical -Horizontal	-Location on Site -Form-Space -Level #	-Element Codes -Shape of Element -Shape of Forms -Strength/Time/Cost -Connectivity of Forms -Supporting Structure -Special Features
	Tools	-Supporting Frame	-Location on Site -Orientation on Site -Level #	-Types of Supporting Frames
Implementation	Robots	-Robot Crane -Mobile Robot	-Work-Space	-Equipments -Types of End-Effectors -Processing Time per Unit
	End-Effectors	-Holder -Welder -Driller -etc..		

Table 1 : Stored and Inputted Data within the CIC Data-Base System.



COMPONENT CODE # 0001130 COLUMN FORM

SUB-COMMPONENTS = { 4 Panels, Reinforcement Bars}

- Shape = { 4-sided column form }
- Size = { Length(1), Length(2), Height }*
- Location on Site = { X-coordinate, Y-coordinate }
- Connectivity + Orientation = { Female [X,-X], Male [Y,-Y] }
- Supporting Structure = { FD-FL, FL-FL, FL-C }
- Form Material = { Aluminum, Composites }

MACHINE = { Equipments, End-Effector, Work-Space }

Figure 2 : A 3D Model Representation of 4-Sided Column Form.

Activity	"Activity Generator" and Its Knowledge

Select a Form (Menu # 5)	Transport_*Type* Form[Level,Stage]
	{
	Type_Of_Robot = Crane or Transportation Robot
	Work_Space = Internal or External
	Site_Storage = [X_s, Y_s]
	Construction_Site = [X_c, Y_c]
	Transportation_Time = T_t
	Transportation_Cost = C_t
	}

Implement a Form (Menu # 2)	Place_*Type* Form[Level,Stage]
	{
	Type_Of_Robot = Mobile Assembly Robot or Crane Robot
	Work_Space = Internal or External
	Placing_Location = [X_p, Y_p]
	Placing_Time = T_p
	Placing_Cost = C_p
	}

Table 2 : "Activity Generator" for Design and Implementation of any Modular Form.

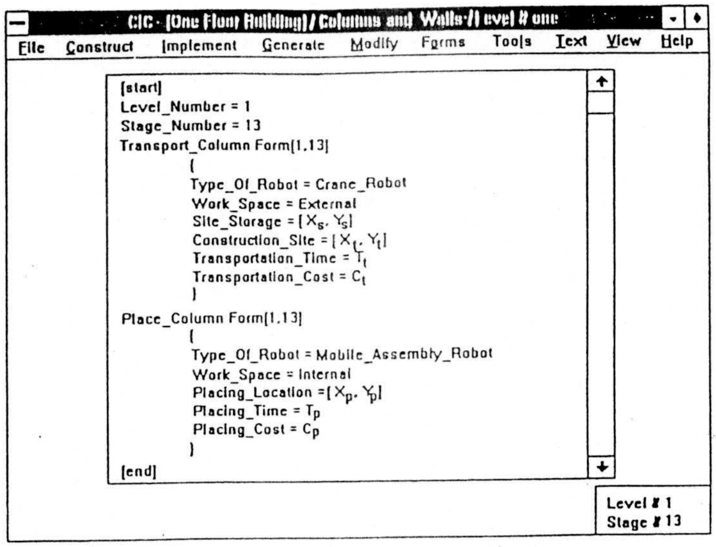


Figure 3 : Process Planning Instructions for a Column Modular Form.

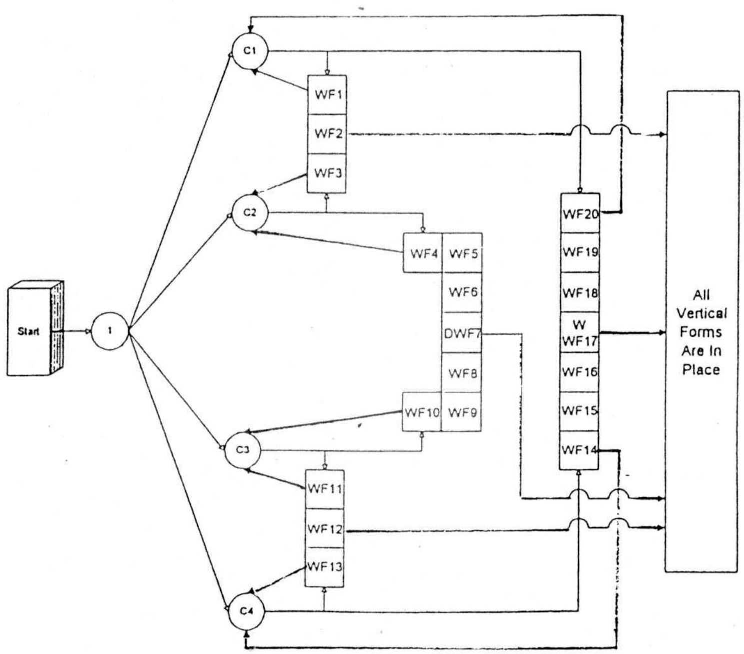


Figure 4 : Activity Network for placing all Vertical Modular Forms.
Where; Ci = Placing Column Form[i]
WFi = Placing Wall Form[i]
DWFi = Placing Door Wall Form[i]

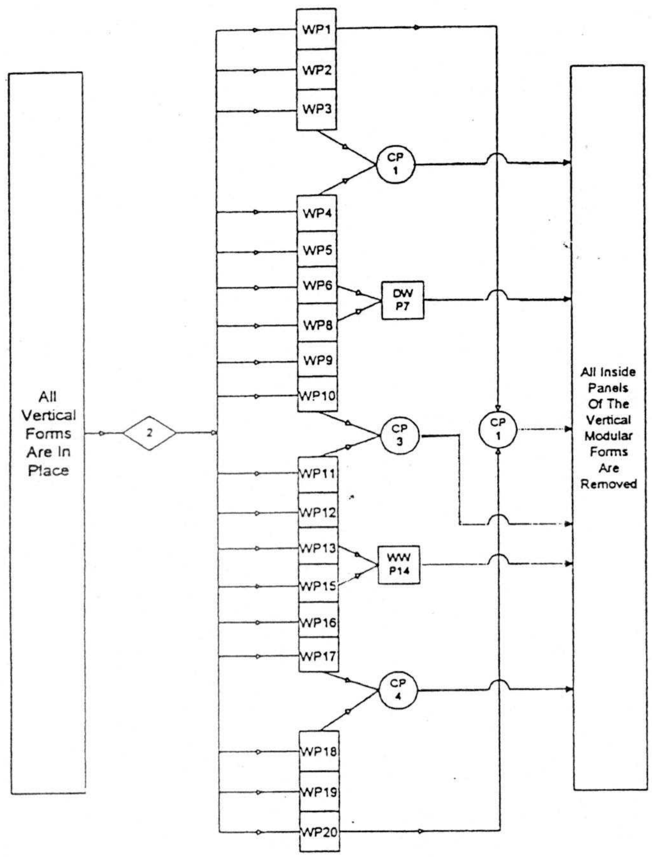


Figure 5 : Activity Network for removing all inside Panels of the Vertical Forms.
Where; WPi = Removing Wall Panel[i]
CPi = Removing Column Panel[i]
DWi = Removing Door Wall Panel[i]
WWi = Removing Window Wall Panel[i]