Automation of modular assembly of structural frames for buildings

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Abstract:
On congested sites in many cities around the world, there is no space available for installing heavy tower cranes and the approach roads are narrow. On such sites, it is desirable to have an automated construction system that can assemble the required components without the use of heavy lifting equipments. This paper introduces a new automation technique which aims to reduce the usage of heavy equipment's in construction projects. The construction is done using automated lifting and positioning systems at the ground level which help in completing the project cheaper and faster. The concept proposed here is a top to bottom construction method using modules of standard sizes. A semi-automatic demonstration prototype of the concept has been implemented in a laboratory. In order to evaluate the potential for saving construction time, experiments were conducted to estimate the time for various operations and these were projected to estimate the time for a typical residential building. It is shown that the structural frame of small buildings can be constructed in a short time, with significantly reduced labor and at low cost. The experimental results show that the total time taken by different people to complete the activities are very consistent and the use of skilled manpower is not essential. With further automation, the time is expected to be reduced considerably.

Keywords –
Automation, Modules, Assembly, Optimization, Automated Construction.

1 Introduction

Automation techniques have been used for both large and small scale construction. An example of a large scale system using heavy machinery is the construction factory system described by Ikeda and Harada [15]. In this system, a factory like structure that surrounds a building under construction includes various robotic systems to automate construction. Very few construction factory systems have been implemented in real construction projects [15]. Another example is the Shimizu Manufacturing system by advanced Robotic Technology (SMART) which is another fully automated construction system for use in high rise buildings [10]. The SMART system was developed until its third generation but its deployment was limited because the system could be used only for rectangular shaped buildings and entire system weighs 1200 tons. It takes more than 2 months for installation and is reported to have low productivity [3]. Most of the above automation techniques rely on heavy machinery like tower cranes. Many authors have reported automation using Tower Cranes [8] [9] [12] to increase the productivity [11] [13]. Even though the construction time can be reduced with these heavy equipment's, many accidents during their use have been reported [1] [2] [14]. There are also several examples of the use of small robots in buildings and construction. A robot used to construct a masonry wall is reported in [7]. A wall climbing robot is described in [16]. Robots have been used to fix glass in buildings. These robots enhance safety by eliminating the need for human beings to do these works [18], but the productivity of these robots are less and cannot be used for large scale construction. Many of these robots are heavy and it is difficult to move them to greater elevations.
Even though, many robotic applications are found in the literature, robotic systems that are appropriate for fast construction of small buildings (up to three floors) could not be found. On congested sites in Indian cities there is no space available for installing heavy tower cranes and the approach roads are narrow. In such sites, it is desirable to have an automated construction system that can assemble the required components without the use of heavy lifting equipment's.

This paper introduces a new automation technique which aims to reduce the usage of heavy equipment's in construction projects. The construction is done using small robots on ground which helps in completing the project cheaper and faster. A demonstration prototype has been implemented using timber modules and the assembly system is controlled by Arduino microcontrollers and sensors. In order to bring out the potential for saving construction time, experiments are conducted to estimate the time for various operations and these are projected to estimate the time for a typical residential building

2 Construction Technique

The usual construction procedure for small residential buildings is bottom up - the ground floor is constructed first, then upper floors are constructed one after the other. As the height increases, the construction cost escalates because of the need to lift materials. In the case of small scale construction, large amount of manual effort is wasted in carrying material to the top floors. The risk of construction at large heights is higher and there are frequent accidents [1].

The idea proposed here is to construct the top floor first and then lift the top part in small steps in order to assemble the modules for lower floors. This will help in performing all the construction activities at the ground floor. This will also support automation since the assembly system can be permanently installed on the ground. These are controlled by using sensors and microcontrollers.

The structure is constructed using small modules that can be easily assembled. For the final automation system, modules will be made of steel bars. Interlocking mechanisms are used to make automation simpler since it requires simple robotic movements for pushing parts and connecting them. However, this requires the parts to be fabricated with much stringent tolerance requirements. In the initial demonstration prototype timber modules have been used because of the ease of fabrication to the required tolerance.

The construction scheme is illustrated in Figure 1. In Step 1, the structural frame for the roof is assembled at the ground level, supported on a series of lifting platforms (Figure 1a). For simplicity, only two sides of the frame are shown in the figure (figure 1a) and only three supports S1, S2 and S3 are shown. These supports are located below the modules M1, M2 and M3, where structural columns will be inserted. In Step 2, all the supports are lifted up by 400 mm which is the height of one module (Figure 1b). In Step 3, the first support is lowered, leaving the frame to be supported by all the remaining lifting platforms. In Step 4, the next module is inserted under M1 (Figure 1c). In Step 5, support S1 is lifted up until the load is transferred to the lifting platform (Figure 1d). Then the next support S2 is lowered (Figure 1e). The next module is inserted under M2 and the process is repeated for all the supports. After the second layer of modules is inserted at all the support locations, the whole frame is lifted up by another 400 mm and the process is continued (Figure 1f).

Figure 1: Construction Scheme

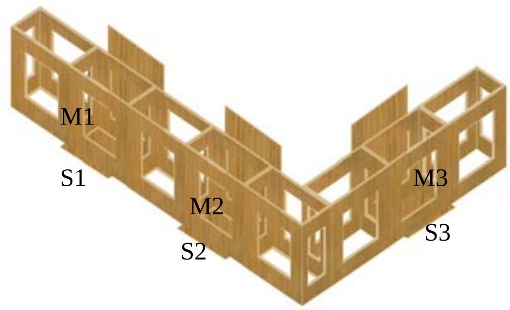

Figure 1a: The top layer of modules are assembled on the ground

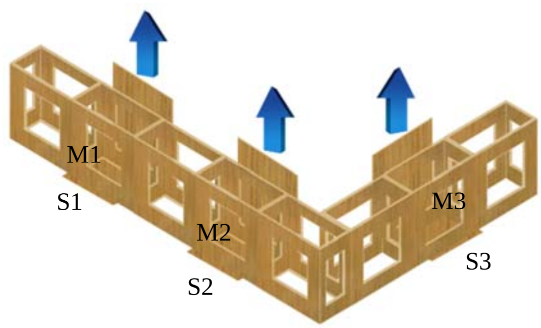

Figure 1b: The assembled layer is lifted up by 400 mm

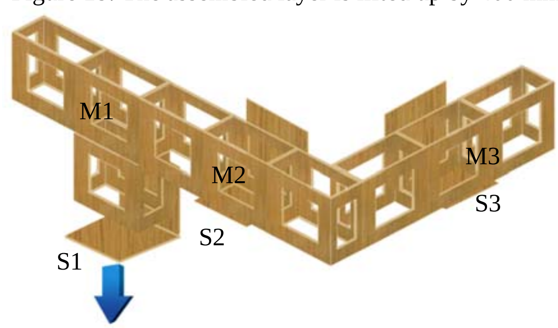

Figure 1c: The lifting platform of the first support is lowered and a new module is inserted underneath

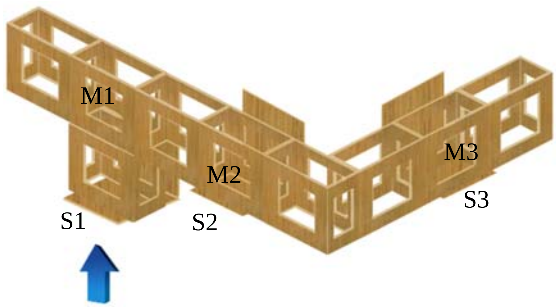

Figure 1d: The lifting platform of the first platform is raised till it takes the load

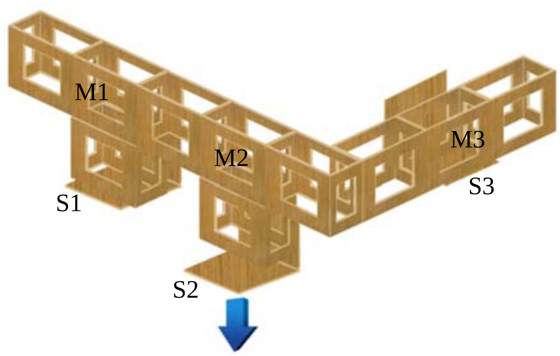

Figure 1e: The lifting base for the second support is lowered and a new module is inserted underneath

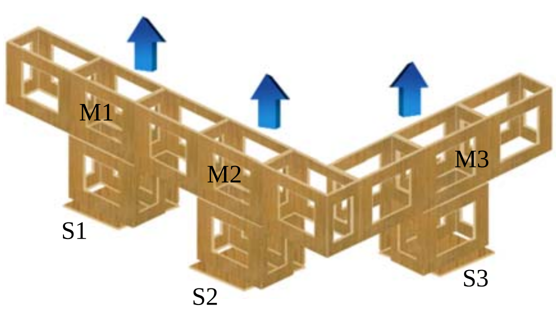

Figure 1f: The process is repeated for all the supports and then the whole frame is lifted by another 400 mm height

3 Initial prototype

The initial prototype is constructed using timber modules and once the feasibility is established, the system will be adapted to use steel modules. The automation system consists of five important parts. They are:

- Frame modules
- Interlocking mechanism
- Lifting system
- Alignment robots
- Assembly robots

3.1 Frame Modules

These are the building blocks of the structural frame and are of standard size. These are prefabricated in factories or workshops under controlled conditions where the required tolerance can be achieved. The strength of the structural frame depends on the strength of the frame modules and the connections. Detailed design of these modules will be performed for buildings of standard dimensions before the next prototype is built. For the initial prototype, predominantly constructability issues are investigated. The wooden modules that are currently used have not been designed to take the full load expected for the building. The geometry of the frame module fabricated for the initial prototype using timber is shown in Figure 2. The dimensions of the module are 400 mm length, 200 mm width and 400 mm height and are made with 20 mm thick timber pieces. The structural frame constructed with these modules are expected to be concealed within the walls of standard thickness used in residential buildings.

Figure 2: Module made of Timber

3.2 Interlocking Mechanism

Interlocking mechanism for connecting modules was designed to make the assembly easier through the use of robots. The "lock" used for interconnecting the timber frame modules is shown in Figure 3. The lock consists of a flat base (flange) with two projections (web) meant to tightly hold together the bars of adjacent frame modules. Pins are designed to hold the locks in position, however, in the initial prototype, the web of the lock is directly screwed to the frame modules. Four frame modules connected using locks are shown in Figure 4.

Figure 3: Lock for interlocking. The space between the flanges of the lock hold together the web of adjacent modules.

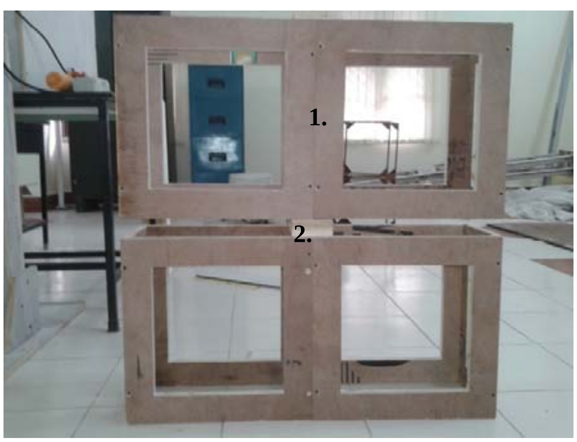

Figure 4: Assembled Modules with interlocks; 1. Module; 2. Lock

3.3 Lifting System

The purpose of the lifting system is to raise the partially assembled frame to the next level so that the next layer of modules could be connected under it. Lifting could be done using hydraulic jacks, linear actuators or hoists. Since the height of the modules is 400 mm, jacks should have a stroke length of at least 400 mm. Jacks with 400 mm stroke length turned out to be more expensive and heavier than motorised hoists. Hence light weight hoists were used in the prototype. Lifting is done using multiple hoists which operate in a coordinated manner. These are placed at regular intervals along the walls to be constructed, within the building foot print as shown in Figure 5. The hoists are supported on a metal platform of height 1.6 m and the platform is designed to ensure stability during the lifting process. Currently six hoists of 2 Tonne capacity are used to construct a wall enclosing an area of 2 m X 1.6 m. Each hoist weighs about 15 kg. Two hoists are installed in the front, two at the back and two on the sides. Their positions have been decided such that the assembled structure is stable with support from five hoists at any time, while the sixth one is being lowered.

During lifting, all the hoists support the currently assembled frame through a lifting base pulled by the steel rope of the hoist. After the frame is lifted to a height equal to the height of the module, one hoist is lowered in order to insert the next module below. After the next module is inserted, the hoist is raised until the load is fully supported at this point. Then the next hoist is lowered and the process is repeated.

The steel rope of the hoist is connected to a lifting base by a metal hook. The lifting base is guided through C-channels on rollers which help in moving the module vertically. The guides in the C-channel help in resisting the horizontal movement of the module and providing moment reaction to the eccentric load. A load cell is placed on the lifting base which helps in detecting the contact between modules and the lifting system and also measures the load taken by each lifting base. The lifting base also has a height sensor. Height sensor is used to control the height to which the module is lifted. These sensors are connected to a microcontroller which controls the actuator which consists of contactors and relays that provide power to the motor of the hoist.

All the actuators are simultaneously operated to lift the structure to a height which is sufficient enough to assemble the next layer of modules below. Then one of the hoists is lowered leaving the structure supported on five remaining hoists. One module is added below the released hoist. This hoist is then operated such that the support touches the newly added module. This contact can be detected with the help of load cell. Then the next hoist is lowered and the process is repeated until all the modules are added below. Then the scheme is repeated till the structure is constructed.

According to the construction scheme, the beams along the roof of the building are assembled first. This forms the first layer of modules as shown in Figure 6. Then the columns supporting the beams are assembled below by inserting the modules one at a time. After the frame is raised to a height above the platform supporting the hoists (1.6 m), the roof slab can be constructed supported on purlins and rafters. Similarly other floor slabs can be constructed at the appropriate stages of lifting. The walls are constructed either immediately after the floor slab is completed or after the entire structural frame is constructed.

Figure 5: Lifting module and Actuator; 1. Metal Frame; 2. Actuator; 3. Steel Rope; 4. Metal Hook; 5. Lifting Module; 6. Load cell sensor

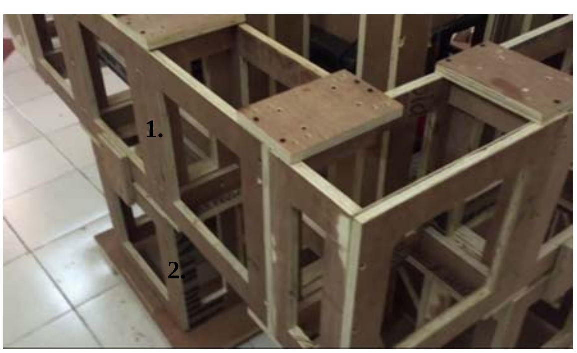

Figure 6: Two levels of Assembled modules; 1. Level 1; 2. Level 2 Modules connected to Level 1

3.4 Alignment robots

The Robot transports the modules and places them precisely under the existing assembled frame. This robot has three degrees of motion. It moves horizontally and vertically for aligning the new module with the existing frame. The robot designed for the initial prototype is shown in Figure 5 and is currently remotely controlled. Current challenges include, installing sensors for aligning the module and controlling its motion automatically. These challenges might be overcome by using image processing sensors. Future work also involves automatically inserting the locks and pins. Currently the modules are manually screwed to the existing structure.

Figure 7: Robot for aligning modules; 1. Robot; 2. Module; 3. Lifting Module

3.5 Assembly robots

Connecting the modules require aligning them precisely side by side and pushing the locks such that adjacent modules are tightly connected. Then pins have to be pushed into the locks to keep them in position. These operations are expected to be challenging because of the uncertainties involved in the fabricated modules. This is topic of future work.

Currently the connections are done manually through screws; work is ongoing to automate this task. Once a layer of modules is assembled, it is lifted to the next level using hoists. Height sensors and load cells are used to control the lifting process. The next layer of modules are assembled under the lifted structure. Custom made robots are used to transport the modules to the required location and align them under the existing assembly. The parts and operations of the initial prototype are described in detail in the next Section.

3.6 Control system

The lifting mechanism is controlled by Arduino controllers. Sensors measure the height through which the lifting device is lifted. Load cells are used to detect contact and the magnitude of the load carried by each support. The output channels of the controller is connected to relays which start and stop the motor in the desired directions.
While the assembly is being lifted, the readings from the height sensor are recorded continuously. The controller stops the motors by sending commands to the relays when the lifting base reaches the required height. Similarly after a new module has been added and the lifting base is raised, the load cell reading is used to detect the contact between the lifting base and the module. When the module is placed on the lifting base and the load cell reading confirms that the load has been correctly transferred to the lifting base, the controller stops the motor of the hoist.

4 System Evaluation

The short term objective of present work is to evaluate the feasibility of the scheme and to establish the potential for saving construction time. The feasibility was demonstrated by constructing the structural frame for a test room of area 2 m x 1.6 m and 2 m height using timber modules.
An experiment was conducted to obtain a realistic estimate of the construction time. Different operations involved in the construction of the test room with the help of 2 workers were repeated several times and the time was recorded.
The experimental procedure involved the following steps:
1. The metal platform supporting the six hoists is installed. The frames for the platform were fabricated in a welding shop and assembled on site with screws. This step was done only once and the time taken for this was noted to be 15 minutes.
2. The initial layer of modules were connected to form the roof beams as shown in Figure 8. This step was also not repeated and it took 45 minutes.
3. The assembled structure consisting of the initial layer of modules is lifted to a height of 0.45 m by the hoists.
4. The lifting base where the next module is to be added is brought down (starting with the first hoist).
5. The spot for loading the timber frame modules is fixed nearly 1 m from the lifting base. The frame module is brought to the lifting base with the robot and the module is placed on the lifting base. The time taken by the robot to reach each lifting base varies since the distances were different. So the average time is taken.
6. The frame module brought by the robot is connected to the module vertically above in the assembled frame. The connection is made manually with screws using a mechanical drill.
7. The lifting base is raised until it touches the newly added frame module.
8. Steps 4-7 are repeated for each column.
9. Steps 4-8 are repeated to fill the next 4 layers resulting in a height of 2 m.

The total time for the completed procedure is calculated by summing up the time taken for all the activities. The short duration activities that are repeated many times during the construction are estimated more accurately by repeating the experiment with different people. The activities that are repeated to estimate the time are shown in Table 1.

Table 1: Activities considered for calculating total time

S.No	Activity
1	Time taken to lift the structure (Step 3)
2	Time taken to lower the first lifting base (Step 4)
3	Time taken to transport a new module using the robot (Step 5)
4	Time taken to connect the module to the frame (Step 6)
5	Time taken to raise the lifting base and make contact with the new module (Step 7)

The experiment was repeated with seven different people who are male college going students who have limited experience with mechanical tools. The total time taken by each person was recorded and is shown in Table 2.

Table 2: Experimental values

S.No	Experiment	Total time calculated
1	Experiment 1	4635 sec
2	Experiment 2	4575 sec
3	Experiment 3	4935 sec
4	Experiment 4	4305 sec
5	Experiment 5	4665 sec
6	Experiment 6	4981 sec
7	Experiment 7	4245 sec

The average time taken to complete the activities in the experiment was 4620 sec (77 minutes). When the time taken by each activity was analysed, it was found that connection and alignment takes most of the total time. Therefore, further automation of these activities are necessary.
The estimated time for activities can be projected to estimate the time for constructing a complete building frame and floor slabs. For illustration, a 3 storey building of plan area (8 m x 8 m) height 12 m is considered. The structural elements consisting of beams, columns, slabs and roof are included in the estimate. The typical time taken using traditional RCC construction was obtained from a local contractor. The time taken and number of labourers required by traditional construction and proposed mechanism are given in Table 3. These estimates show significant reduction in construction time using the automated procedure.

Table 3: Comparison between Traditional construction and proposed mechanism

	Proposed Automation Model	Typical Construction
Time of Construction	30 Hours	45 Days
Number of Labours	2	10

In the real time construction, the building frame is made of steel modules. The steel components are welded into the module shape in a pre-fabrication site. These modules can be directly used in the construction of the building frame, same as the timber modules. The modules can be connected by welding or by connecting them with steel locks using bolts. The likely weight of each module is around 3.9 Kg and the weight of each steel lock is around 2 Kg. The same proposed scheme of mechanism can be used to build the building frame. The above illustrated 3 storey building of plan area (8 m x 8 m) height 12 m require around 1248 modules and 2496 steel locks. The total weight of structure will be around 9859.2 Kg.
Because of the scaling of the modules the scheme of the mechanism will not be changed, only the number of lifting bases required will only change depending on the scale of construction.

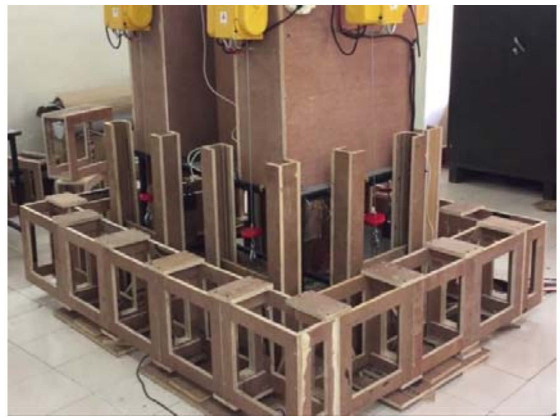

Figure 8: Assembled layer of modules

5 Concluding Remarks

The proposed automation system can easily be dismantled into small components and can be transported by one or two people in small vehicles. The cost of the system is very less when compared to existing automation equipment's. It has been demonstrated that the structural frame of small buildings can be constructed in a short time, with less manual labour and at low cost. The experimental results show that the total time taken by different people to complete the activities are very consistent and the use of skilled manpower is not essential.

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