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AUTONOMOUS SOLUTIONS FOR DESIGN AND IMPLEMENTATION OF MODULAR STRUCTURES

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Abstract. Our objective with this paper is to analyse and explore emerging autonomous solutions for designing and implementing modular structures. Modular structures have been in use since the 1950s, so the concept is not new to us. Historically, the popularity of modular structures peaked following catastrophic natural disasters or wars, in areas that required rapid rebuilding. However, modular construction somewhat fell out of favour afterward. Nowadays, its popularity is resurging, becoming a notable trend once again. The robots employed in modular construction offer distinct advantages over those used in traditional construction, with streamlined tasks and enhanced efficiency. In this paper, we plan to analyse drones, loaders, cranes, and worker bots. These robots will serve various roles, including observation, construction, organization, and excavation. Furthermore, we aim to integrate these robots with cutting-edge technologies such as artificial intelligence, augmented and virtual reality, the Internet of things - IoT, cloud services, and building information modelling - BIM.

1. Introduction

The world around us is undergoing rapid transformation, with constant introduction of new technologies, gadgets, and services. While modular construction is an age-old concept, it remains a relevant and promising trend. The integration of autonomous robots into this field is poised to shape the future and revolutionize the construction industry. Our objective with this concept is to offer an alternative to traditional building methods, enabling the construction of buildings, schools, hospitals, and even entire neighbourhoods in a matter of weeks. The planning process will involve a team of engineers, whose designs will then be scrutinized by a BIM software packet. The BIM packet will meticulously assess the project for errors, potential conflicts, and mechanical or electrical issues that may arise during or after construction. Drones will serve as primary observers of the construction site, equipped with cameras and sensors to monitor progress in real-time. Following them, excavation robots will take charge of digging for the foundation of the structure. The worker bots will possess the capability to dismantle modular structures as per the community's requirements. Coupled with AI, cloud services and BIM, they will play crucial roles in the project. BIM, when utilized alongside augmented reality (AR) and virtual reality (VR), will provide a comprehensive visualization of future projects, and offer real-time insights into the construction progress.

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Keywords. Modular construction, Autonomous robots, Drones, Artificial intelligence, IoT

2. **Modular construction**

While we have referenced modular construction several times, we have yet to provide a clear definition. Modular construction entails the assembly of a building off-site, within controlled factory conditions, utilizing identical materials and adhering to the same codes and standards as conventionally constructed facilities. Modular structures can be either permanent or relocatable. Broadly speaking, modular construction can be categorized into three main types:

- Type I: 2D Panels or Planar construction – these panels are used mainly for walls and are cheaper to transport from the assembly site to the construction site.
- Type II: 3D Modules or Volumetric units – these can be parts of a room or full rooms.
- Type III: Hybrid construction – this is a mixed use of linear elements, panels, and modules to create a mixed construction system.

All three types of modules can feature full insulation, along with preinstalled electrical and mechanical components, based on specific requirements. Other variations of modular constructions include Cladding panels, which serve as prefabricated façade elements attached to the building to encase it, and Pods. Pods are non-structural modular units, such as toilets and bathrooms, directly placed on the building`s floors. Modular construction offers significant advantages over tradition construction, and some of them are:

- Lower cost;
- Less waste during construction process;
- No weather – related delays;
- Better sustainability and efficiency;
- Structures are built faster.

In addition to advantages, we also need to talk about disadvantages. There are a few of them, and they have been worked on over the past few years. Some disadvantages of modular construction are:

- Limited design flexibility;
- Transportation;
- Site access;
- Initial investment;
- The resell value of the structure is lower than that of a traditional construction.

The challenges that modular construction faces at the moment are industry adoption, workforce training, regulatory framework, permitting frameworks, and a small number of suppliers. To address these challenges, efforts are underway to make modular construction more mainstream and affordable. The last bit of information that we will present here, is its future possibilities. Virtual and Augmented Reality, Artificial Intelligence, 3D printing and Automation are technologies which are used elsewhere and are planned to be incorporated in modular construction in the near future.

The modular construction we are going to explore in this article is Type II: 3D – Volumetric modules with a steel frame. The time comparison between a traditional and a modular structure is shown in Figure 1.

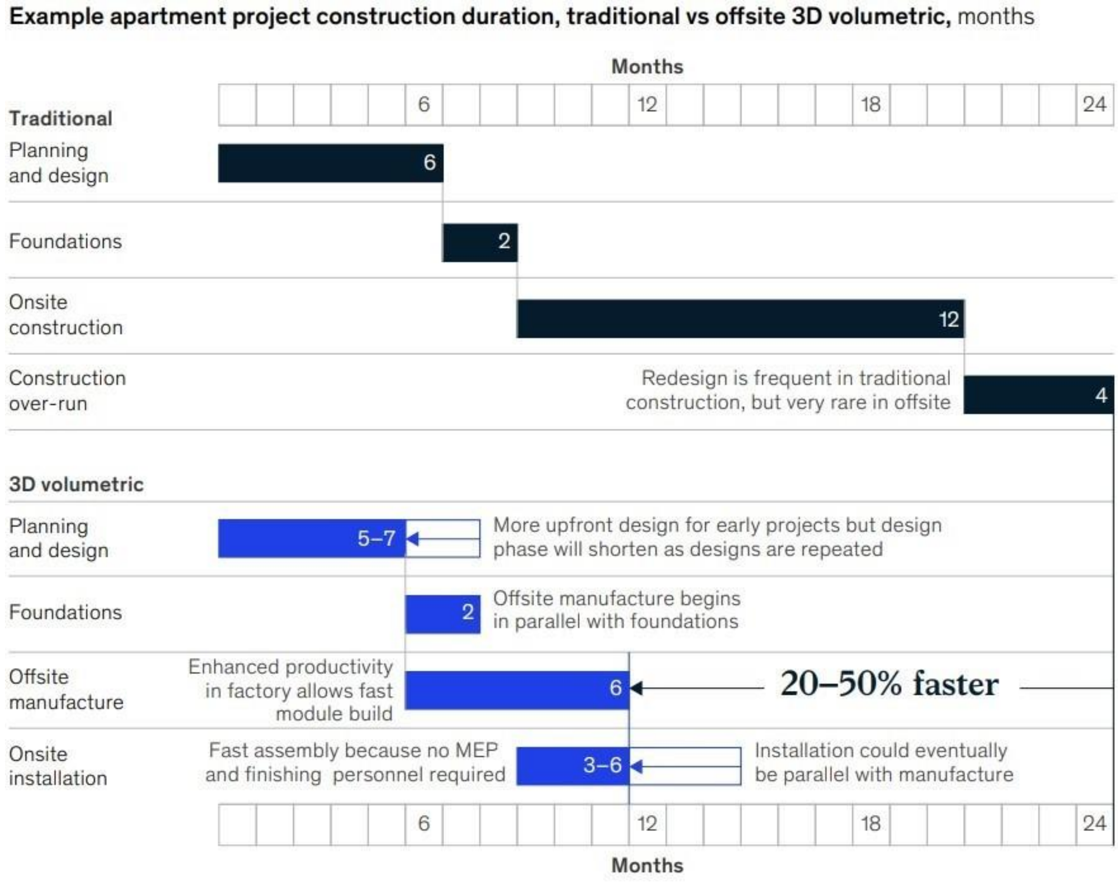

Figure 1. *Time comparison between a modular construction and a traditional construction [5]*

3. **Robots and their programming**

The robots that we will be using are going to be autonomous and controlled by AI. Given the heavy-duty nature of construction machinery and their high-power demands, we will not propose transitioning to an all-electric machinery. Instead, we will enhance existing machines by retrofitting them with automatic remote-control systems. This can be achieved by integrating actuators to execute the functions typically handled by operators. Economically and ecologically, this approach of adding controllers and actuators is more viable. It allows us to utilize our familiar machinery efficiently. The autonomous fleet required to complete our projects consists of:

- Surveyor drones
- Excavators, Front and backhoe loaders, Scooptrams
- Motor graders, Compactors
- Cranes and Heavy-duty forklifts
- Worker bots

On this list the worker bots are the only unspecified robots we have. The term "worker bot" refers to a robot capable of autonomous movement within a construction site and performing diverse tasks. This category of robots is relatively new, with practical implementation emerging only recently. In this article, we will highlight several worker bots that are particularly useful in modular construction. Notable examples include Komatsu, Theometrics, Doxel AI, Baubot, OKIBO, Jailbot (from Hilti) and ULC Robotics.

The sensors we will be using on the machines are shown in Figure 2. The camera, inclination sensor and pressure sensor are self-explanatory. The lidar is used for creating a 3D image of its surroundings using lasers and RTK stands for real time kinematics. This is a GPS receiver capable of RTK and it has a positional accuracy of 1cm (centimetre).

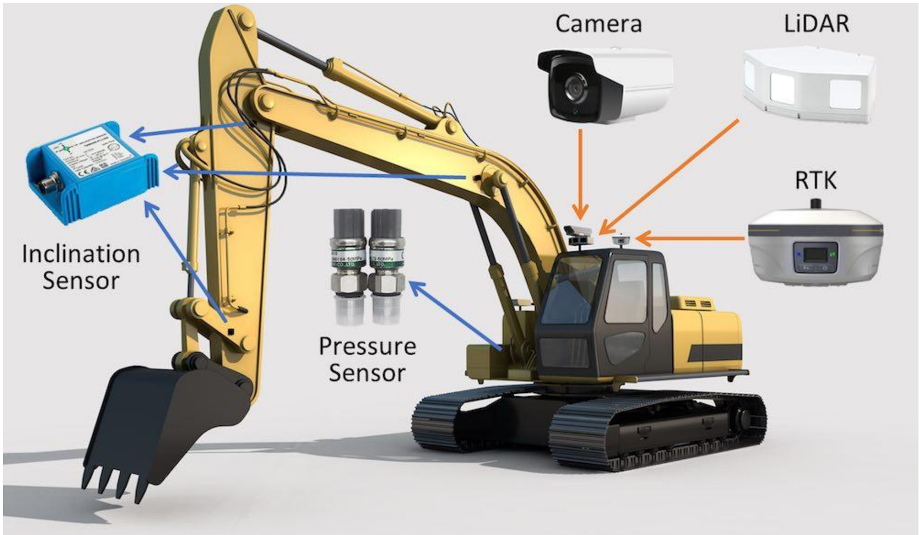

Figure 2: *Excavator with sensors for autonomous operation*[1]

We will utilize drones from upper mid-tier or high-end brands, enhancing them with an advanced camera and 5G communication capabilities to connect with an on-site

[1] https://www.mdpi.com/2075-1702/12/3/173

computer. This computer will be linked to the cloud, and it will access the BMI project there, enabling seamless transmission of vital information to the drone. The drone will then relay this information to the relevant machinery; if we need to intervene for some reason, we can send information directly from the computer to the machines and robots. The AI responsible for controlling the robots will reside in the cloud, with only essential data transmitted to the on-site computer. To train the AI in operating the machinery, we will conduct simulations with varied parameters in a virtual environment. Throughout the learning process, one of the AI`s key programs will be the “Critic”, a sub-routine tasked with evaluating solution quality. An important detail here is that we need positive feedback; as we know, more often than not we need to compromise certain things in order to get the desired result. Positive feedback serves to determine where and to what extent compromises should be made. In figure 3 we can see how the information is being shared between the cloud, the construction site, and the upper management.

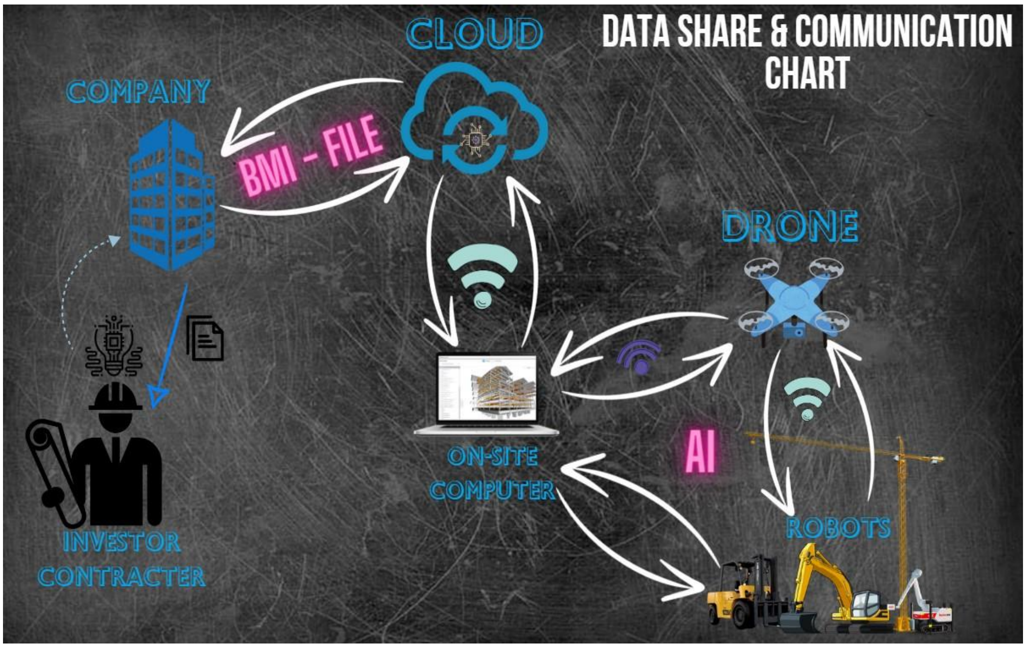

Figure 3. *Communication between the cloud, the construction site, and the upper management*

The investor can ask for certain changes from the company that undertakes the realization of his project, and they should receive regular reports about the progression of the project. The company uploads the BMI files to the cloud, from which the on-site computer accesses them and conveys them to the drone. The AI is communicating with the cloud through the computer. On the site the operator behind the computer should be a BMI manager. A BMI manager is usually an engineer with knowledge from multiple areas and some prior experience.

4. **Process phases**

The construction process is structured into six distinct phases, each named to reflect its specific workload and tasks.

Phase I: BIM – This phase deals with designing the structure and planning for the following phases. The name of the phase is an acronym for Building Information Modeling (BIM). BIM is defined as a process involving the generation and management of digital representations of the physical and functional characteristics of places and structures. We can think of BIM as an advanced hybrid version of Computer Aided Design (CAD) and Computer Aided Planning (CAP). Building information models are digital representations of physical structures that can be shared, extracted, or exchanged among stakeholders. These models play a crucial role in supporting the decision-making processes throughout the lifecycle of a built asset, from design and construction to operation and maintenance. The complexity of our BIM project can be represented in levels:

- Level 0 BIM: This level is only for 2D drawings, and it does not require any collaboration.
- Level 1 BIM: On this level we use 2D models for drafting production information and some 3D models for concept work. Here the data is shared on a common data environment (CDE) that is managed by the contractor.
- Level 2 BIM: Here the teams are working on multiple 3D models and are collaborating even more closely.
- Level 3 BIM: On this level, every team works on the same 3D model.
- Level 4,5,6 BIM: The level here depends on the addition of scheduling, cost or/and sustainability.

Using BIM can aid us in detecting collisions and identifying the locations of discrepancies. Thanks to BIM, we can create a roadmap with checkpoints that lead to our goal. The checkpoints are here to help us move through the process smoothly. Notable checkpoints can be the starting date, the date when the foundation is placed, the date we install the modules and so on. For improved access and safety, we can put the BIM files on the cloud. The BIM project can be changed in real-time by engineers, depending on some internal or external situation. Additionally, we can track the progress of our structure by using Internet of Things or various sensors. We plan to use this feature to create better communication between the cloud and the robots on the site. To ensure we do not have any issues with our BIM files, on the account that multiple software packets can be used to create a single BIM project, we need a common data environment or CDE for short. One way to eliminate this problem is to use software packets by one developer, such as Autodesk. Autodesk offers a variety of BIM software packets, with seamless communication between them.

Phase II: Drone Overview – In the second phase we start implementing the autonomous surveyor drones. The drone is the first robot deployed on the construction site and it has two main and one additional task as an organizer. Its main tasks are observing and mapping. While observing, the drone collects information about the construction site and processes it. When the drone switches from observing to mapping, it starts to share the information about the site with the other robots and tells them where to go and what to do. This is its organizer task in play. The first information the drone collects is about the readiness for excavation. Let us say, the site has some leftover debris from a structure that was demolished. The drone scans the area with debris and marks it for cleaning. The next step is to relay this information to an excavator or a scooptram (for this project we are not including autonomous trucks). After every successful action executed by the robots, the drone is notified and it comes around to observe the site again. If the site is cleared, the drone maps the starting point for the excavator to start digging to place the foundations. The drone is not airborne all the time. We are using the drone every hour to check the progress of current tasks and the state of the site. The drone will start flying every time another robot reports a problem or a successfully executed task. The AI communicates with the drone through the on-site computer and it exchanges information such as progress, current tasks being carried out, and any changes made to the original BMI project.

Phase III: Excavation – The third phase is where we introduce the robots that prepare the site for our structure. In the second phase we mentioned the use of excavators and scooptrams to clear the site of debris and other junk. After cleaning we can proceed with digging for the foundations; this is a job for the excavators and the loaders. The information that is required by excavators and loaders, such as where to dig and the size of the hole, is transmitted from the surveyor drone. In some cases, if the drone is unable to send or receive information from excavators and loaders, we can use the on-site computer. After completing the task, the surveyor drone comes to check on the progress and to grade the accomplished task.

Phase IV: Foundation and Structuring – In the fourth phase we start to place the foundations. In our case, we are talking about a steel foundation and a steel frame. The foundation is placed in the hole by using loaders with the grappler attachment to hold them in place and after this we fill the hole with cement. Afterwards, we can use motor graders and compactors to harden and level the cement. From here we start the second part of this phase. The points where we need to attach the steel beam to create the frame for the modules are already placed. The beams are carried by a crane to the connection point and the worker bots adjust and attach the beams to the foundations and later to each other. The last step of this phase is surveying and reporting on the finished task.

Phase V: Module Arrangement – In this phase we present the modules to the site. The modules we will be using are 3D – volumetric units with preinstalled plumbing and electricity. Here we need to position and fixate the modules in the steel frame. The modules arrive on trucks and they are unloaded with heavy-duty forklifts. The forklift takes the module to its designated position in the frame. The worker bots come in play here and attach the module to the frame. After attaching each frame, the drone checks the connection points and the position of the modules. If we need to add more steel beams for a higher or wider structure, we can repeat the second part of phase IV.

Phase VI: Quality Control – In the last phase we are using the surveyor drone to do a quality check on the structure. The quality check consists of a visual comparison to the BMI project on the cloud, the quality of the connecting points, the number of critical points, and an overall efficiency score. The efficiency score is a function of accessibility, power usage, functionality, and thematic aesthetics. After the drone uploads the score to the cloud, the engineers can do a manual control and compare it to the drone’s score. Throughout a series of projects, the drone will learn and give a more accurate score in the future.

5. **Conclusion**

We can safely assume that in the near future, we will witness a drastic increase in autonomous robots and some intense AI advancements. All these improvements are coming to the construction site. The part we covered here is only a scratch on the surface for what we should expect. Finding alternative ways to build, communicate, and innovate will improve this initial design. For the moment, we can start by adding a small team of autonomous robots to some construction sites and we can collect data from it. The first robot present on the site would be the drone. Unlike our designed drone, this prototype will have a task to only observe the workers and their progress. Step by step, the design presented here can be perfected to a fully autonomous construction team, with fast and efficient decision making, dedicated to steady progress toward its goal.

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