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A framework for a digital system to aid informal self-construction

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Abstract. Assisted self-construction has been proclaimed by the UN Habitat as one of the most affordable methods of providing sustainable housing. Self-construction in informal settlements is analogous with incremental development, where design and construction occur in simultaneous waves. However, unassisted self-construction often produces housing of substandard quality owing to a lack of knowledge and resources. This paper hypothesizes that the core factor leading to substandard housing in informal self-construction is an information and communication gap in the existing process. In order to identify the gap, a mapping and analysis exercise is carried out that identifies the focal points where the informal system deviates from the formal, the decisions that influence these deviations, and the impact of these deviations on the overall output. The paper develops the framework for a smartphone-based, digital technical aid system, that fills this information and communication gap and provides construction guidance to owner-builders without compromising the nonlinear nature of incremental development.

Keywords. Informal Construction; Self-Construction; Digital Technical Assistance; Digital Fabrication.

1. Introduction

Self-construction is the practice of actively participating in the construction of one's own home. In informal settlements across the world, most homes are self-constructed incrementally, starting from a shelter built using temporary building materials such as bamboo and fabric, and gradually upgrading to a permanent dwelling [*Pucca in Hindi*] using bricks, stones, and reinforced cement concrete (Bredenoord and Lindert, 2014; Turner, 1977). While such practices match the socioeconomic and affordable limits of the dweller, the lack of construction-specific knowledge pertaining to materials, structural composition, and proper techniques often results in a substandard quality of the homes built (mHS Citylab, 2011; Turner, 1977). This led to the development of the concept of technical assistance, wherein organizations and institutions provide specialized knowledge and technical support to the owner-builders in the construction process (Harris, 1998).

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Although technical assistance caters to the knowledge gap in informal self-construction practices, it is limited in its capacity of achieving economies of scale and enforcing a faster rate of production of homes (Burgess, 1985). This limitation drives the adoption of other models of production of affordable housing, such as state-sponsored subsidized mass housing. However, standardized mass housing fails to address the varying socioeconomic and autonomous demands of the dweller (Turner, 1977). The need for a system of technical assistance that retains the autonomy of dwellers in self-construction while achieving a faster and economical rate of production can be developed with the application of digital technology. The economical aspect of such a system can be justified in the capacity of digital systems to achieve economies of production instead of scale, by replicating the process and not the product. To satisfy these constraints, this paper proposes a digital system of technical aid developed using ubiquitous and accessible technology such as smartphones.

Another limitation of current practices of technical assistance is its tendency to formalize the informal construction process (Burgess, 1985). Bredenoord and Lindert (2014, pp. 56-57) define the differences between formal and informal construction. Formal construction practices follow a linear process: planning and design are succeeded by construction activities followed by occupation by the dwellers. Informal practices, on the other hand, follow a non-linear process that begins by occupying vacant land followed by incremental upgrading and retrofitting to build a permanent dwelling. Burgess (1985) demonstrates how current practices of technical assistance tend to provide design-centric formal solutions that do not address the variable demands of informal dwellers. Moreover, such practices offer one-time assistance during construction, which limits its application in incremental development. This paper hypothesizes that the reason for multiple repairs and substandard quality of structures produced is an information and communication gap in the informal construction process. Instead of formalizing the existing process, this research examines the use of digital technology to fill the information and communication gap without changing the nature of incremental development.

This research, thus, aims to capture this non-linear nature of informal construction in a digital system of technical assistance that guides owner-builders in the self-construction process. The architecture for a low-cost, smartphone-based digital system is designed that gathers information from an owner-builder's environment, analyzes the information, and provides guidance to self-construct a quality output that is aligned with the owner-builder's requirement.

2. Related Works

This section reviews existing literature on digital technical aid systems, human-centered digital fabrication, and the application of smartphone sensors in position finding and communicating guidance with users. The proposed system builds upon the research reviewed here to develop the final system architecture.

2.1. DIGITAL TECHNICAL AID SYSTEM

While technical assistance for informal construction is a much researched area, there is very little work supporting a digital system of aid. Mehra et al. (2017) developed a digital project management system that provides information regarding material quantities, labor costs, and project timelines. The research focuses on supporting the lack of knowledge regarding material and labor costs. However, it does not provide construction activity related guidance to the workers. This paper builds on the above work and explores a system that can provide structural and spatial guidance in addition to material-specific knowledge.

2.2. HUMAN-CENTERED DIGITAL FABRICATION: GUIDED CONSTRUCTION

While most digital fabrication projects apply robotics in construction, a relatively new branch of study looks at the development of Human Computer Interface (HCI) systems to actively guide humans in construction. Yoshida et al. (2015) explores a digital system operating on real-time tracking and feedback using a depth camera and projection mapping. The system guides humans in an additive construction workflow. The proposed research builds on the concept of tracking and feedback applied in the above work to provide tailored guidance to owner-builders.

Additionally, in the field of active communication as construction guidance, Lafreniere et al. (2016) explore the use of wearable technology such as smartwatches in large-scale collaborative construction. In the field of Augmented Reality, interactive tools such as Fologram and state-of-the-art technology using a mix of visual and Inertial Measurement Unit (IMU) sensors have also been applied in guiding humans in construction (Gramazio Kohler Research, 2019; Newnham and Beanland, 2018). While most such studies use cost-intensive hardware that is not feasible in an informal context, this research adopts the technological concepts of the above studies in a low-cost setting.

2.3. ACCESSIBLE DIGITAL TECHNOLOGY

López et al. (2016) show how accessible, open-source technology such as ARToolkit can be used to gather positional information in digital fabrication systems. Such augmented reality applications are increasingly being developed for smartphones (Henrysson and Ollila, 2003). Additionally, Umek and Kos (2016) confirm the accuracy of smartphone gyroscopes to generate 6-degree coordinate information in a mobile biofeedback system. The system proposed in this research uses an array of smartphone sensors explored in the above works, such as camera and IMU sensors, to develop an accessible, low-cost hardware set-up.

3. Methodology

In order to develop a digital system that captures the non-linearity of the informal construction process, it is imperative to understand how the implicit decisions taken by owner-builders influence the construction process, and how it differs from the formal construction process. While Bredenoord and Lindert (2014) have highlighted the overall differences between the formal and informal process, this research focuses solely on the construction aspect. Foremost, a mapping exercise is carried out that measures the informal construction process against the formal process to understand where deviations occur. Following that, the implicit decisions that build up these deviations are mapped.

While the system developed in this paper is generic and can be applied in any context, the local construction technology studied in this research is context-specific. For the purpose of this research, case examples from India were taken. To map the formal process, on-site visits of residential construction projects from the cities of New Delhi and Guwahati, India were undertaken. The projects were chosen based on a higher degree of application of local construction technology such as water levels, plumb bobs, etc., instead of high-end technology such as lasers. These local construction technologies most closely resembled the tools and construction technology applied in informal settlements, making the comparison more accurate.

For mapping informal construction, research on incremental construction done by Patel and Kunte (2011) in Mumbai, and King (2016) in Delhi were used as references. Additionally, pilot projects applying self-construction practices done by mHS Citylab (2011) were analyzed to understand the influence of local contractors and changes in family circumstances in the construction process.

Since the informal process is incremental in nature, information from one construction activity serves as feedback for the onset of a forthcoming activity. To best understand this process, the data gathered in the mapping exercise is analyzed through feedback loops to identify the information and communication gaps in the current process. These feedback loops also help analyze the non-linear (concurrent design and construction) nature of informal construction. This exercise is carried out using case examples from the work done by Patel and Kunte (2011), King (2016), and mHS Citylab (2011).

The analysis done using feedback loops helps develop the requirements for the digital aid system. The system architecture is then developed with the view of filling the information and communication gap in the current process, and provide structurally and spatially optimized, context-specific guidance to the owner-builder.

4. Mapping the Informal Construction Process

The studies on informal construction mentioned (see Section 3) show that socioeconomic conditions, lack of technological, material, and financial resources, and inadequate knowledge of construction are some of the major factors influencing informal construction. This mapping exercise identifies the focal points in the construction process where such factors intervene. The mapping exercise was done by breaking down the construction process into smaller modules such as marking reference levels for construction, excavating foundation, building walls, building roof and floor slabs, etc.

Table 1 presents the excavating foundation construction module. This module was chosen for illustration owing to the fact that in a formal construction process, this is the first step that deliberates on a target design. This marks the point where the informal process begins to clearly deviate from the formal process through the implicit decisions taken by the owner-builders.

Table 1. Mapping the informal construction process for excavating foundation.

FORMAL		INFORMAL		
Construction Sequence	**Alignment and Traversing methods**	**Alignment and Traversing methods**	**Deviations from Formal Sequence**	**Decisions Leading to Deviations**
Mark functional areas on ground	Centre-to-centre distance marked using thread mesh	*Not Applicable*	Areas are not pre-determined, and built as required. Locations of all wet functions are not known	In incremental construction, different functions are added when there is availability of resources which limits prior planning
Calculate depth level of foundation from road level (reference)	Check digging level using water level	Inconsistent use of method	Inconsistent method. In some cases, road level is marked arbitrarily or eliminated all together	The method to mark and traverse level depends on the mason, and is sometimes done based on observations rather than accurate data
Stick 4 inch stakes on the ground	Check orthogonality by measuring diagonal with threads	Inconsistent use of method	*No deviation observed in construction sequence*	
Mark walls on the ground with chalk	*Not Applicable*	*Not Applicable*	*No deviation observed in construction sequence*	
Mark column centre	Thread mesh and plumb bob to determine centre	*Not Applicable*	Excavation is done for brick stepped footing. Columns are built at grade.	Knowledge gap: most masons are not aware of the techniques to construct a framed structure, and rely on existing practices.
Mark column footing profile using starter	*Not Applicable*	*Not Applicable*		
Excavate marked areas to required depth	Desired level of excavation measured using water level	*Not Applicable*		

As seen in Table 1, both the formal and informal process are broken down into two parts: the first column delineates the construction sequence while the second column captures the technology and tools applied for the measurement of construction elements. Capturing the data in this manner helps in understanding how to extract machine-readable data from the process. The construction output for every step, as well as human action involved, can be converted into machine-readable data using coordinate and sensory information.

For the informal process, the parts that deviate from the formal process have been mapped. The reason and external factors influencing each of these deviations are then demarcated (see Table 1, column 5). Identifying the focal point of deviation in the informal process and the factors causing the deviations help in understanding the method and type of information impacting informal incremental construction. To understand how this information, or lack thereof, impacts the overall outcome, the next section looks at the process through feedback loops.

5. Feedback Loops in Informal Construction

Feedback loops are a chain of causal connections within a system where some or all of the output produced in one part of the system returns as input information. In an incremental construction process, since subsequent layers of construction in the form of upgradation or repairs always build on the construction output of a previous stage, it essentially functions as a feedback loop.

This section analyzes the informal construction process using feedback loops. Patel and Kunte (2011), and King (2016) demonstrate how the incremental self-construction process works. The incremental process begins with building a temporary shelter to occupy a vacant plot. This is followed by gradual upgradation when resources are available. Patel and Kunte (2011, p.58) highlight two types of incremental change: recurring changes from annual repairs and upgradation when there is a change in resources or family circumstances.

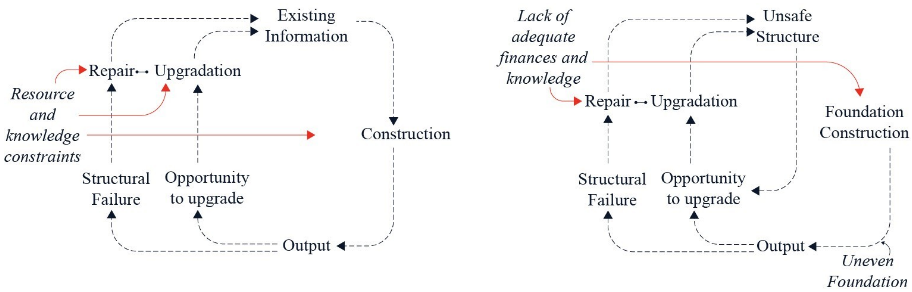

Figure 1. (Left) General feedback loop for incremental self-construction; (Right) Feedback loop for foundation construction.

Figure 1 (Left) shows the general feedback loop for incremental construction. The output that is affected by resource and knowledge constraints becomes the input for the next step of upgradation or repair. In this manner, a flaw in the structure in the initial stage of construction can lead to overall structural failure.

Figure 1 (Right) draws on a case presented by Patel and Kunte (2011, p.64), where uneven foundations laid by workers who lack construction knowledge crack easily. This creates a recurring expense for the dweller. Even in the case of repair, the persistent lack of knowledge would result in an unsafe structure that when upgraded would multiply the effect of the damage leading to overall structural failure.

Analyzing the informal construction sequence through such feedback loops highlights the impact of missing information in incremental development. This, coupled with the mapping of the informal process (see Table 1), forms a comprehensive roadmap for developing the digital system architecture.

6. Proposed System Architecture

From the analysis done in Section 4 and Section 5, it is evident that for any system to comprehensively capture the informal construction process, the following conditions are imperative:

1. Gather all information related to the construction process: construction method, tools and techniques, in addition to circumstantial information that can impact the process such as a change in family situation, lack of resources, and affordable

limits.

2. Analyze all information gathered simultaneously since it is evident from the feedback loop analysis that any part of the process affects the overall outcome.

Based on this analysis, contextual guidance can be generated by the digital system and provided to the owner-builder during construction.

6.1. SMARTPHONE INTEGRATION: FILLING THE INFORMATION GAP

The smartphone is the core part of the digital system that works as the communication medium between the worker and the backend analysis that computes and provides guidance. Smartphone sensors can be deployed to gather required information about the construction process and environment, as discussed in Section 2. Two types of data are required to comprehensively capture the entire construction environment:

1. **Point cloud data of construction elements**: Scanning all construction elements will enable the system to measure errors in spatial and structural composition. As seen in the case of Figure 1 (Right), scanning the foundation while constructing would capture the unevenness, and proper guidance could be delivered to eliminate this error. Camera sensors can be deployed to track construction elements using ARToolkit, to generate point cloud data. This method also ensures that only selected and necessary information is fed into the system, reducing the load on the backend analysis program.
2. **Sensory data related to owner-builder's activity**: Gathering data regarding the owner-builder's position, the rotation and angular motion of their hands used in construction can help gather information about activities undertaken. This information can be used to provide context-specific guidance. IMU sensors can be deployed to gather this data.

Additional information regarding circumstantial changes can be fed into a smartphone application interface in a boolean data format.

Guidance can be relayed to the owner-builder using inbuilt smartphone vibration sensors and Interactive Voice Response. Additionally, a layer of video-based guidance can reduce the knowledge gap further.

6.2. BACKEND ANALYSIS: PROVIDING CONTEXT-SPECIFIC GUIDANCE

In order to cater to simultaneous design and construction activity, the backend program needs to run a constrained analysis of the information gathered. This analysis should be run against the following three criteria:

1. **Procedure**: This criterion ensures that crucial steps of the process are not overlooked, such as measuring alignment and orthogonality, curing process for concrete, etc., by gathering relevant data regarding owner-builder's activity.
2. **Structure**: This criterion ensures the structural integrity of ongoing construction by gathering data on the alignment of structures, the structural composition of reinforcements, material composition, and interfacing elements.
3. **Spatial**: mHS Citylab (2011, pp. 13-14) highlights how self-constructed dwellings compromise on spatial quality. This criterion analyzes the quality of built spaces against configuration, functional layout, and environmental quality.

The role of the backend analysis is to generate guidance that is tailored to the construction activity. As such, a pre-established database comprising all types of local construction technology is required. Such a system would ensure that the guidance provided is not just for permanent construction, but also for spatial and structural optimization of temporary or other vernacular methods of construction.

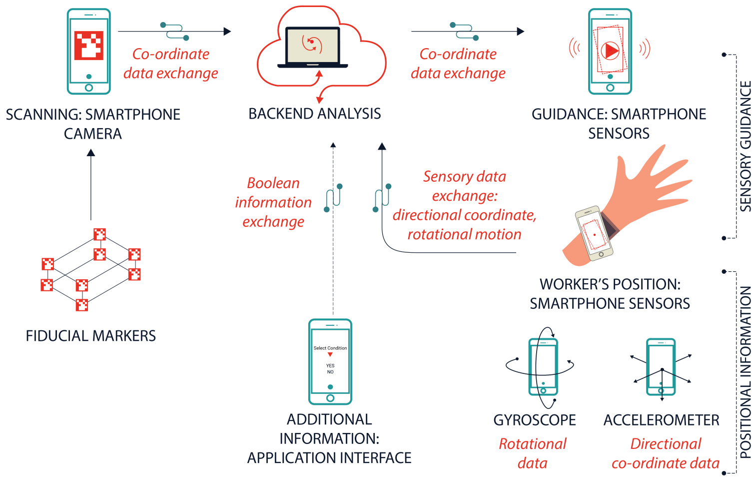

Figure 2. The System Architecture.

The overall system architecture is illustrated in Figure 2. The Backend Analysis is at the core of the system, which analyzes the information gathered from scanning construction output, the owner-builder's motion, and additional circumstantial information. The guidance is then relayed to the owner-builder through the smartphone.

7. Limitations

The research methodically develops a framework for the digital aid system based on the analysis of existing systems of incremental self-construction. In this section, the limitations of the research and implications for future work are discussed.

First, the data to map the construction process was primarily acquired through secondary methods. Since incremental construction takes considerable time to materialize and is dependent on external factors such as the availability of resources, it is difficult to capture the process first hand. Most such studies are based on interviews of the dwellers, and crucial information might be lost in the process.

Secondly, since the local construction techniques across the global south vary greatly, the study becomes highly context-specific. While the method of capturing data can be replicated, the architecture of the backend program may differ slightly based on the geographical location from where data is acquired.

Additionally, while the research builds upon a range of studies that demonstrate the application of smartphone sensors in scanning and guidance technology, it does not test a prototype for the proposed system. As such, the physical limitations of the systems are yet to be determined.

8. Discussion

Despite the limitations discussed above, the contribution of this research in devising a method to actively aid informal self-construction without formalizing the construction process holds value. Most technical assistance practices and digital fabrication aimed to provide affordable housing is output-oriented. In order to minimize the error in the output, they tend to eliminate the information and communication gap in the process. While this ensures quality output, it offers one-time assistance that fails in an incremental setting. This research illustrates a process-oriented approach that fills the information and communication gap in the existing processes instead of eliminating it. Additionally, a digital system of aid ensures continued guidance that is independent of geographic and temporal constraints. The scope of future work for the system is discussed below:

Scaling across the global south: Since the backend program runs its analysis on a database of local construction technology, this model can be scaled and replicated across the global south by updating information on local technology pertaining to a specific location.

Applying Systems Theory: This research demonstrates a systems-based approach in identifying the information gaps in the existing scenario, by applying feedback loops to analyze the incremental process. This can be further amplified by exploring how actions at every step of the process affect the outcome and reinforcing the backend analysis to counter these actions to prevent failure in the output.

Training unskilled workers: This system can be used as a training module for unskilled workers. Since the proposed system is capable of identifying the knowledge capacity of workers by gathering information about the worker's activity, it can provide tailored guidance to train the workers.

9. Conclusion

This paper presents a framework for a smartphone-based, accessible digital aid system for informal self-construction that addresses a nonlinear, incremental method of construction. In the method presented here, design and construction occur concurrently, replacing the formal linear method of design preceding all forms of construction activity. The central argument of this paper is that while most forms of technical assistance for self-construction adopt a deterministic approach towards eliminating structural failures, this contradicts the principles of incremental construction and reduces the autonomy of the owner-builder in the construction process. Through an analysis of the informal process measured against formal processes, this research identifies that the primary cause of structural or spatial failures in the output is an information and communication gap in the construction process, that when filled can aid an incremental manner of development without compromising the quality of the output. To achieve a real-time flow of information and communication in the construction process, the application of digital technology is sought. In order to deliver this, the paper proposes a framework for a digital system that explores the application of low-cost digital technology such as smartphone sensors to gather information from an owner-builder's construction environment, analyze it against three parameters: informed process, structural integrity, and spatial quality, and provide sensory guidance through a smartphone to guide the owner-builder in the construction process. The resultant system is a form of technical aid that ensures the non-linearity of incremental self-construction while maintaining quality output.

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