AUTOMATED CONSTRUCTION RESOURCE LOCATION TRACKING TO SUPPORT THE ANALYSIS OF LEAN PRINCIPLES

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ABSTRACT

This paper presents a research framework and preliminary experimental results to automated construction resource (workforce, equipment, materials) location tracking for the purpose of advanced lean planning and rapid decision making. Based on the statement “what can be measured, can also be changed”, the research hypothesis was formulated that advanced automated remote sensing technology can measure and improve work site performance and assist decision making. The initial research scope focused on testing emerging real-time location tracking and data analysis technology (Ultra Wideband and Video) applied in capital intensive construction site settings.

A literature review is presented on existing observation techniques that have been used in the analysis of lean construction operations. The research framework and technology in context to lean construction is explained next. To better understand construction operations – and in particular construction site activities related to safety and productivity – location and movements of workers, equipment, and materials were recorded in real-time. Preliminary results to field experiments demonstrate the feasibility of tracking construction resources accurately and in real-time. An outlook and applications are presented of how the collected resource trajectory information can be used in project decision making. It is envisioned, that once site resource data is collected, processed, and linked to existing schedule and work task planning, the information can play a vital role for rapid implementation of lean principles in the operational environment of construction sites.

KEY WORDS

Decision Making, Productivity, Safety, Tracking, Ultra Wideband, Workforce.

INTRODUCTION

Construction research has been increasingly focusing on discovering synergies between the adoption of lean practices and information and sensing technologies (Navon 2007). The use of information and sensing technologies are in particular beneficial to lean practices when they improve the flow of construction processes by

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identifying non-value adding activities that can be eliminated, cycle-times that can be shortened, and errors that can be omitted. Overall, by adapting technologies that assist decision makers during the planning and/or execution stage, errors, rework and variation can be minimized (Sacks et al. 2010).

Lean thinking and the use of technology is not new to construction. In practical field applications, for example, Global Positioning System (GPS) for earth material grading or Automated Machine Guidance (AMG) have greatly reduced rework (Hildreth 2003, Hannon 2009). During the project planning and life-cycle stage, for example, Building Information Models (BIM) easily allows to detect design errors such as clashes or other variations and smooth the flow of production (Sacks 2010).

In summary, lean construction concepts as introduced by Sacks (2010), for example, generally profit from using technology. As technology typically provides valuable data sets, advanced decision making becomes feasible. The analysis of field data for work flow stability, communication between teams, lean production planning and pull flow control, elimination of waste, and unobstructed flow and transparency of information can become possible.

Past research (Diekman et al. 2006), however, has shown that the degree of realization and the potential of technology as they are implemented in construction field applications are far behind other industries. As the International Group for Lean Construction describes, the success of "lean" in construction is likely to be much greater when a diverse number of technology systems become an integral part of the lean thinking process. Furthermore technology can provide the data sets required for solid decision making. Thus, technology can be geared towards a continuous improvement strategy (IGLC 2010).

Many lean principles relate to the research presented in this paper: Product flexibility and process transparency (reducing over-production and exceeding customer and client understanding and needs), waiting and idle time (reducing of the incidence of non-value added activities and process variability), transportation (reduction of cycle time, delays, or handling more than once), inventory (in stock rather than just-in-time), motion (reduce non-value adding paths), over-processing (work on the product that adds no value), and tools and information (at the right place and time with the required quality, reduce defective units or rework).

Applying remote sensing as data collection tool can allow improving work flows during the various phases of the project delivery. It can also enable to see bottlenecks, how they originated and developed over time, and how they eventually were solved. Important lessons learned can be gained and to prevent similar events from happening again.

Although this research is too recent to address and validate some or all of these lean principles in construction directly, it demonstrates specific examples and early work for measuring resource (workforce, equipment, material) presence, work task productivity, and as-planned vs. as-built status. This is particularly important when it comes to assessing work site safety and waste reduction that are some of the most frequent and time consuming work tasks of site safety and management personnel.

A range of methodologies and research and experimentation tools exist for the incremental improvements that lean thinking demands. The research that is presented throughout the following sections of the paper focuses on: Methodologies and tools to study and optimize workforce, equipment, and material flows, inventory management, and control of construction processed applied to live construction field operations.

BACKGROUND

Project monitoring and control, including progress tracking and resource utilization tracking, constitute distinct components of measurements. Specifically, progress tracking measures quantities installed while resource utilization tracking measures consumed work hours as well as the way by which such work hours were spent (Zhai et al. 2009). Current techniques for site operation analysis, as described by Goodrum et al. (2009) focus on the monitoring of construction progress and the measurement of work task productivity, but are heavily based on manual efforts or at best partially automated. Similar (manual) steps are taken to analyze for lean principles, including for site safety and security control (Goodrum et al 2009). Recent advances in the construction industry and applied research focused on the utilization of Radio Frequency Identification (RFID) and Ultra Wideband technology (Ergen et al. 2006, Grau et al. 2009, Teizer et al. 2007), laser scanning (Bosche and Haas 2008), vision (Brilakis et al. 2008, Golpavar 2007, Kamat and Martinez 2001, Lukins et al. 2007), 4D CAD modeling (Fischer and Drogemueller 2009), simulation (Kamat and Martinez 2001), and work sampling (Goodrum et al 2009). Wireless and vision based sensing of site operations have beem applied on several jobsites today, and come at low, medium, and high cost, each has distinct benefits (Bohn and Teizer 2010). Once geospatially registered, wireless and vision based sensing can link to existing project level information (Golparvar 2009), such as pre-existing CAD models. Several case studies have demonstrated the success of these technologies in construction applications, i.e. tracking construction productivity using radio frequency (RF) tagging of construction resources (Grau et al. 2009).

While the core sensing infrastructure may include a variety of sensors, fundamental work concentrates on the creation of data processing algorithms for site operation analysis. Following the framework architecture, updated project level information (schedule, CAD site layout plan, GIS model) as a base for progress evaluation, can be geospatially linked to sensing data from vision or other sensor based resource tracking. This can be precisely interpreted by relating the spatial source of the data to the as-built model. These contain rich planning and execution information of the ongoing activities to be measured. Also, information on construction methods provides the ground for measuring detailed work hour utilization of a construction activity in addition to the total work hours consumed, resembling the connection between as-built model and progress tracking.

As several case studies related to resource tracking have shown, technology is then integrated into the framework if it comes at acceptable cost (hardware installation, maintenance, and anticipated benefits through data processing). The complexity of handling large data sets, however, has prevented significant impact of (semi-) automated data collection and analysis techniques in construction.

In summary, the overriding goal of this research is to lay the foundation for a scalable deployment of a presented framework for automated sensing for site operations analysis and validate it through preliminary field experiments. We show in Figure 1 the core focus of the research within the context of a lean site operations analysis and feedback framework. In essence, project level information is available for supporting lean progress tracking and resource utilization tracking. Observations, if they use technology, are based on remote sensing technology based on vision, GPS, and other technologies. A major obstacle for practioners though is the limitations of these existing approaches in automated, effective and (near) real-time data analysis. In conjunction with the data produced by other sensing modules, data only then becomes useful if it will establish factual records that can be either archived or immediately used for decision making. When measuring processes, information is generated typically when answering the questions "why" and "how" did this (project specific) situation arrive. Resource and time allocation play a critical role in this paper, and some examples are presented in Figure 1 of how the answers to these questions can be used to provide immediate useful feedback to the practioners at the project level. Data that has been process to information and has allowed measuring the process, can also be used to create long-lasting knowledge that may have impact on future projects.

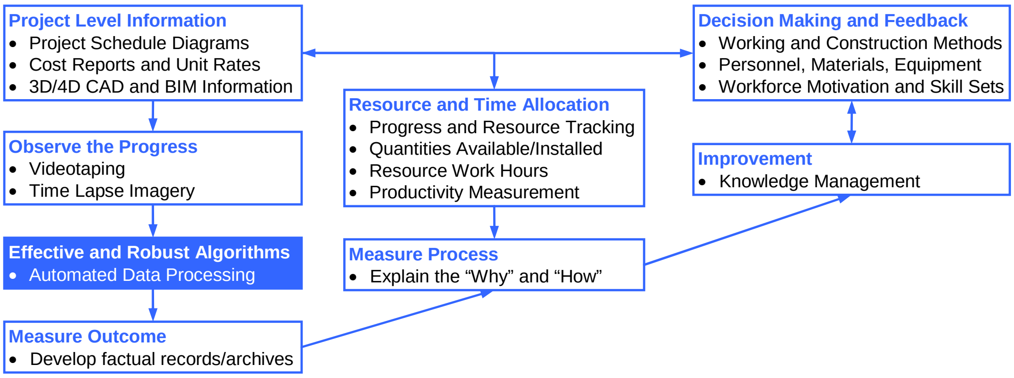

Figure 1: Framework for Automated Sensing and Decision Making for Site Operations Analysis.

MONITORING AND CONTROL TECHNOLOGIES AND RESEARCH NEEDS

What is lacking from this body of existing research on data processing techniques is long-term temporal tracking of construction assets and workforce for the analysis of lean site operations. While research in construction has focused on specifics subsets of the overall procedure regarding automated or semi-automated operations analysis, both an architecture for generating more complete analysis of construction site operations through sensors, and the selection, validation, and verification of the appropriate computer algorithms are needed. The presented work seeks to demonstrate some initial steps taken towards this goal.

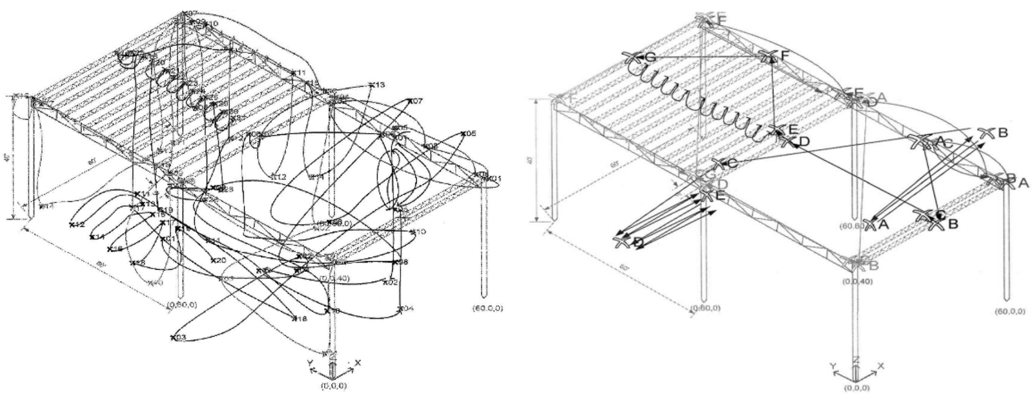

Figure 2: Manual Video Analysis of Structural Steel Assembly: Observed vs. Ideal Trajectories (Diekman et al. 2006).

Vision-Based Observations

One of the most economical ways to track progress automatically is by recording video or taking images. This approach is not new to construction. Diekman et al (2006), for example, used manual video recording and interpretation to successfully demonstrate non-value-adding paths of construction workers (see Figure 2). Unfortunately, manual efforts that go into accurate recording and precise interpretation of the collected visual data can be very high, especially over long time periods. Automated methods would positively benefit this research area; however, the main challenge in vision-based approaches is precisely the automated extraction of progress information from time-lapse photographs or videos of construction site environments.

Promising research in optical-based progress monitoring has focused on the comparison of as-planned vs. as-built infrastructure and structural modeling in augmented reality (Kamat and Martinez 2001, Golparvar et al. 2007), defect detection (Gordon et al. 2003), and three-dimensional modeling (Bosche and Haas 2008). Instead of representing the as-built environment, this research delivers preliminary understanding of the construction process by directly providing trajectory information of construction resources (personnel, equipment, and material) for analysis of site operations.

The increased need for- and use of- advanced sensors on the construction work-site, coupled with the massive amount of data collection associated with the sensors, a fortiori demands the use of automated or, minimally, semi-automated methods (Navon 2007). The field of computer vision specifically deals with the collection, processing, and visualization of data associated with the three-dimensional world (Forsyth et al. 2000). Depending on the sensor and intended data, a variety of techniques exist for processing imagery and video (Hartley and Zisserman 2000, Yilmaz et al. 2007, Geronimo et al. 2007, Viola and Jones 2004, Pollefeys et al. 2008).

Real-time Location Tracking

Technologies such as Global Positioning System (GPS) and Ultra Wideband (UWB) provide location information. Commercially available UWB systems allow recording position and timestamp values of tagged resources (personnel, equipment, materials). Previously manual trajectory analysis identified when workers entered or approached areas where they should not be in, such as confined spaces or restricted areas (Teizer et al. 2007). Identifying such cases in real-time can lead to real-time alerts to warn workers of danger. These new technologies can be used to collect an unprecedented data set, both from training and on-the-job environments. Such data sets can include the analysis of productive, safe, and secure worker behavior as well as simulated events including precursor events for hazardous conditions that are commonly observed on job sites.

RESEARCH OBJECTIVE AND SCOPE

The research objective was to automate the detection and tracking of worksite resources (personnel, equipment, and bulk materials) on construction sites using remote sensing technology and to tie the collected data to critical information and tasks associated to the work plan. The characteristics of the recording equipment to be used were presumed to be known and limited to site specific characteristics. In addition, site characteristics of the construction operations to be analyzed included operations in lay down yards, building construction, and other activities in civil environments. The sites had mostly open areas and line-of-sight access such as roadside construction. These are conditions where it was typical to have heavy machinery working alongside personnel, or to see collections of bulk materials on the premises awaiting integration into an as-built structure.

Due to the limitations of line-of-sight sensors, the preliminary steps of this work did not cover interior work or other similar construction operations with massive occlusions arising from the built structure. The work also did not seek to handle adverse visual conditions due to poor weather. Precipitation such as rain and snow was known to affect vision based sensors; however, the construction operations of interest also typically halt under such circumstances.

FIELD TRIALS AND PRELIMINARY RESULTS

This section details the research tasks that were performed in support of the research objectives. Details to research activities regarding data collection and analysis are presented in the following sections, followed by brief discussion on the results and findings, and a conclusion of how to integrate the presented efforts in lean construction engineering and management tasks.

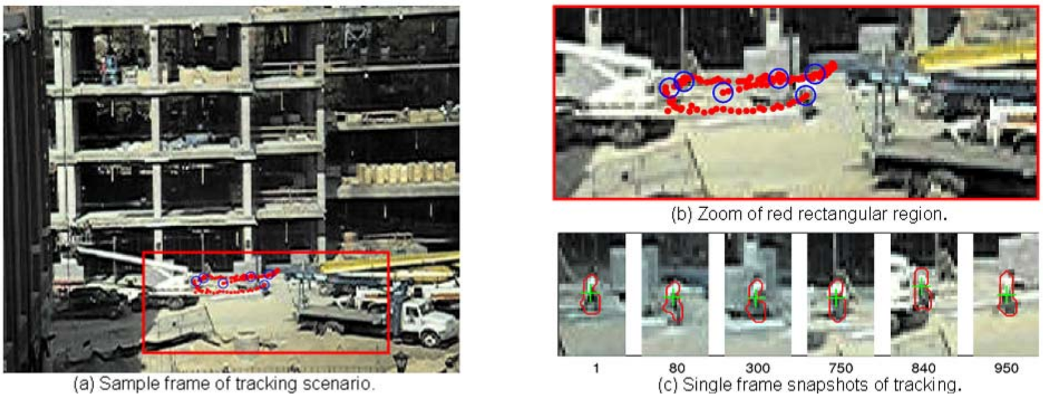

Figure 3: Tracking Personnel using Wide Field-of-view Camera Surveying.

VISION-BASED MONITORING AND TRACKING

As discussed in the background section, preliminary research efforts have led to moderate success in tracking personnel on the construction site using wide field-of-view cameras. The assessment of lean principle though has often been performed through manual data collection and analysis efforts. Significant cost and time savings can be expected if the data collection and analysis process can be automated and integrated in the decision making framework.

Due to the large intended visual footprint, vision cameras do not provide detailed information regarding sufficiently small track entities such as personnel. In order to track small targets in such a large visual field-of-view, this research has had to improve upon existing tracking algorithms. The digital colour version of Figure 3 depicts the most recent results on tracking ***individual and multiple workforce*** under such conditions. The algorithm used to track personnel relies on a machine learning method known as Kernel Principle Component Analysis (KPCA), which is used to learn the spatial and appearance information associated to each person to track. While kernel methods are known to increase execution time, our research has identified strategies for optimizing execution. Open problems that still need resolution and validation include long-term temporal tracking of personnel, both as well-separated individuals and as multiple interacting personnel.

Given that the construction environment necessarily includes ***heavy equipment*** at many scales, of which most are involved in the construction of the as-built structure, it will be necessary to also track the operation and movement of each of these pieces of equipment. Machines found on a construction worksite exist at many sizes relative to humans, from small (i.e., skid steer loaders), to medium (i.e., excavators), to large (i.e., pile drivers and cranes). Given the distinct dimensions and appearances, a fundamentally different strategy will be utilized for tracking equipment. Nevertheless, the principal concepts regarding machine learning and density matching learned from personnel tracking will serve to inform the proposed equipment tracking algorithm.

It also is common for large infrastructure construction projects to contain on pre-built ***materials or large volumes of bulk materials*** onsite for installation. The supply and depletion rate or visible existence of these materials provide time-stamped evidence regarding the state of construction activities, their location and trajectories used (see digital colour version of Figure 4). Identifying and tracking resource existence and/or volume over time will thus enable automated production control. As the awareness of the completion rate associated to work packages is important, project managers and field practioners can be alerted if the depletion rate falls below threshold values. To successfully track the changing supply levels of bulk materials requires algorithms capable of detecting and segmenting these materials in sensed images. While detection algorithms are needed to identify the existence of these materials, segmentation algorithms are proposed to maintain track of the time-varying material supply.

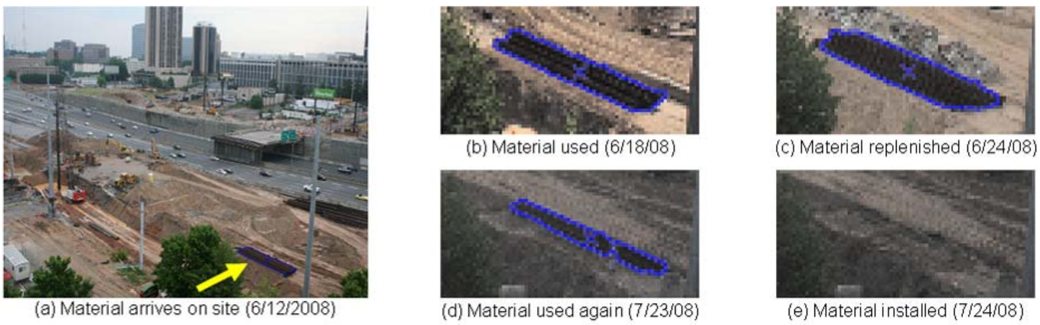

Figure 4: Automated Pile Material Supply Tracking using Time-lapse Images.

WIRELESS REAL-TIME LOCATION TRACKING

Ultra-wideband (UWB) is similar to RFID technology, but provides real-time location tracking data to a resource that is equipped with a UWB tag. UWB is thus fundamentally different to RFID as it works on a short pulse radio frequency (RF) waveform which is based on the time-domain principles of electromagnetic theory (Fontana 2003). Compared to other technologies like RFID or ultrasound, UWB has shown to possess unique advantages like high temporal resolution along with a high bandwidth, which are ideal for ***precision localization applications*** (Teizer et al.

2007). Higher range, measurement accuracy and immunity to interference from rain, fog or clutter make UWB ideal for use in construction environments. UWB signals are considered to be immune to multipath interference, and hence have an edge over other technologies in a cluttered and dense communication environment. Personnel, equipment, and materials inside a lay down yard, for example, can be tagged with UWB tags to track the location of each of these resources in real-time (see Figure 5).

A typical UWB localization system comprises of (i) a central hub processor and computer interface with (ii) receivers that are capable of instantaneous ultra wideband field detection while being connected to the hub using CAT-5e shielded cables, and (iii) tags that are attached to the resources which are to be tracked (see Figure 6). The location of each tag is calculated based on synchronizing the arrival signal using the time-of-flight principle. Signals between receiver and a tag can then generate real-time two-dimensional positioning data if at least three receivers are used. Real-time 3D location sensing requires at least four receivers, preferably at locations with significant difference in elevation.

Figure 5: UWB Tags Attached to Personnel and Construction Machinery.

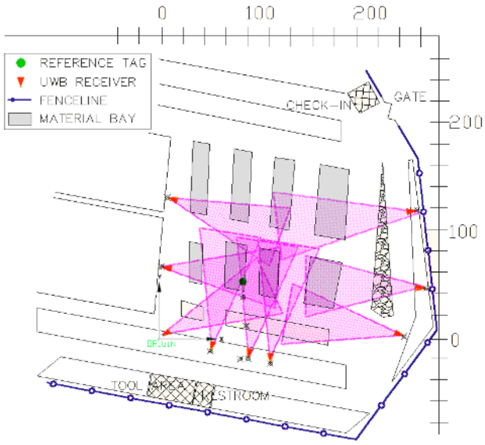

Figure 6: Layout of Ultra Wideband (UWB) Receivers in Lay Down Yard.

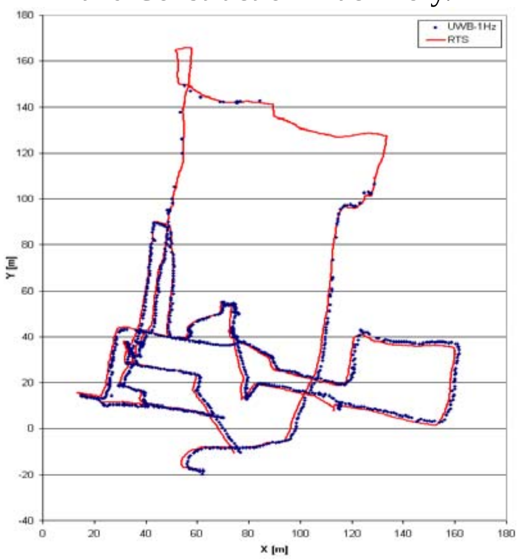

Figure 7: Plot of Geospatially Referenced Trajectory Data of a Construction Worker using UWB and (RTS) measurements.

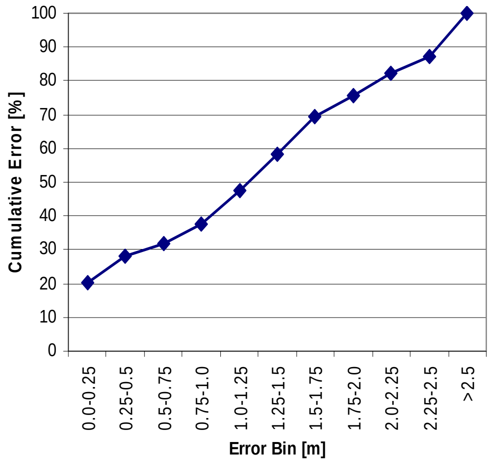

Figure 8: Error rate of Ultra Wideband (UWB) compared to Robotic Total Station (RTS) measurements.

Preliminary results in Figure 7 illustrate that precise location tracking of construction resources becomes feasible. Ultra Wideband (UWB) positioning data was compared to precise positioning data of a 1" Robotic Total Station (RTS). The positioning error in a lay down yard of steel frames is illustrated in Figure 8. In this preliminary experiment, close to 90% of the positioning data of a construction rigger was within 2.5 meters of the location that the robotic total station had measured. Experiments in other work environments resulted in positioning errors of Ultra Wideband technology as small as 0.25 meter. Depending on the work environment, setup, and upfront calibration of the technology, positioning errors have been observed that are typically less than 2.5 meters.

CONCLUSIONS

Advances in technology have made it possible to implement cost-effective vision and wireless tracking systems in construction applications. As demonstrated in field trials, vision and wireless sensing system can provide robust (near) real-time tracking data to multiple construction resources. At the same time, data processing techniques evolve that have the potential to give decision makers tools in their hands that were not available before. Preliminary experimental results to locate and track materials and pieces of equipment were presented that can play a particular important role in applying lean strategies in field decision making. Some limitations and benefits to each technology were highlighted that remain and need to be solved, i.e. line-of-sight and multipath signal interference, robust and real-time data processing algorithms. Additional research is necessary to overcome these limitations.

Future research must address the following research questions in the field of lean construction: How can lean measures be facilitated by technology? How, and how much, do information and sensing technology systems contribute to improved process flow, reduced rework, etc.? What kind of information and sensing technology tools are needed? What information and sensing technology implementations are appropriate for what lean measures?

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