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A survey of automation technology for realising as-built models of services

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Abstract

As-built documentation is a contractor's certified record to what was built and it is extremely important to the owners for the purpose of maintenance, major renovations, and demolition, especially for critical but typically hidden services infrastructure. Unfortunately, the value of the final delivered as-built documents are commonly limited significantly by leaving their creation, as an afterthought, to the end of a project. As-built documentation is also frequently left in the hands of inexperienced workers or apprentices to correlate original drawings, documented change requests and as-built input from the sub-contractors (when it exists). This often results in large un-correlated collections of in-accurate, incomplete information with limited utility for describing exactly what was built. This approach also misses the opportunity of using continuously updated as-built documentation to manage on-going work, coordinate trades and catch deficiencies early enough to avoid expensive rework. Partially automating the maintenance of as-built documentation would make it feasible for construction management to use it as a tool during construction and deliver it in a useful form to the client upon completion. This paper reviews some past and current automation technologies used in realising as-built models of buildings with a focus on how they are applied to modelling building MEP (mechanical, electrical and plumbing) services, and includes some early results from exploratory work assisting in creating as-built models for an ongoing construction project.

Keywords: As-built documentation, MEP, automation techniques, technology survey, BIM, CAD

1. Introduction

Most significant capital projects require the builder to provide as-built documentation to owner/operators as part of the contract. Currently, this task is usually left to juniors or apprentices and to the end of job. Furthermore, the documentation is often delivered as an uncorrelated collection of paper documents with different sub-contractor's as-built notes written on them combined with records of the change orders and sometimes the general contractors (GC) own observations notes. As-builts are also known as “redlines” due to the common practice of using red pencil to mark the changes on construction documents. Delivered in this way the documentation is not very useful. Pettee [25] does a good job of documenting these practices and makes the observation that significant effort and organisation is required with current practices and processes to create useful as-built documentation. Cheok et al. [17] note that on a typical $100 million construction project approximately $2 million goes to material tracking, monitoring progress of construction activity and creation of as-built documentation. Pettee [25] goes on to observe that unless these documents are constantly updated during construction the GC cannot benefit from them and that they are not a very closely reviewed deliverable, thus, to the GC, creating as-builts is not a value adding task.

Although “Measured Drawings” are also referred to as as-built drawings, the term is more applicable to recording existing conditions for existing structures for the purpose of renovations, re-modeling and historical restoration projects. Many older buildings or facilities lack accurate or any documentation of structural or service installations which are required before project plans are prepared.

Given floor plan drawings of a construction project, measured or from the architect, mechanical, electrical and plumbing services (MEP) consulting companies prepare the MEP drawings to show the 2D layout of building service endpoints such as the location of all HVAC equipment, thermostats, diffusers, air return grills, electrical fixtures, switches, panels, plumbing fixtures, and sprinklers, The drawings may not show the exact location of cable trays, electrical cable routings, drain pipes, etc. unless explicitly demanded in the contract document. The MEP drawings are then followed by general contractors, electrical, mechanical and plumbing contractors to do their work on a project. Any changes from the proposed layout are to be recorded during the construction and the engineering drawings are red-lined to reflect the as-built conditions.

Since, several contractors usually work simultaneously to install the MEP services, the current common practice involves regular trade coordination meetings being held on site to identify and resolve problems so that the installation of one type of service does not interfere with another. Quantifying the costs of field conflicts is difficult due to the variations in projects but Riley et al. [26] note that ~80% of the costs are not recovered by the contractors and that simple coordination costs range from $0.5 to $2.0 a square foot. Pettee [25] points out that if up-to-date as-built documents existed during construction they could be used to coordinate trades on site and avoid late identification of clashes that can cause scheduled delays or worse, rework orders. Ideally, from the perspective of the GC, as-builts would track the current state of the building during the construction process and serve as the basic input for daily/weekly planning meetings.

From the perspective of the building owners and operators, final as-built drawings would show the net result of all change orders and show the dimensions, locations and assemblies/components actually installed. They would serve as basic documents for major renovations, large maintenance activities or use in facilities management.

As the magnitude of the resources currently required to deliver good as-built documentation during a project is a major hurdle to their development and active use, the rest of this paper reviews and presents current technologies used to automate parts of the process of creating as-built models of services in constructions and make suggestions for future tool development from a pragmatic usability perspective. As mentioned earlier, this work will focus on ways to improve documenting as-built conditions of MEP services to support coordination during construction and a reduction in field conflict costs.

The next section presents current, and some ongoing research into, processes and technologies used for creating as-built models. The final section looks at the future and how technologies can be used to reduce costs and time requirements to make as-build documentation and support construction activities.

2. Current Process and Technologies

Before reviewing the technologies used to create as-built documentation, the two ends of the spectrum for delivering this documentation should be briefly described. Common today is the delivery of an un-correlated collection of documents (mostly paper) including change orders and red-line drawings from various contractors. This is the easiest to deliver, yet the least useful. The most advanced form is the use of Building Information Models (BIM) where the state of the construction is captured as semantically rich models (i.e. building elements can be identified as such and not just pure geometry) over time, hence as 4D models [20], and sometimes along with other relevant data such as serial numbers or operational characteristics of equipment for nD BIM models. These multi-dimensional models can support advanced applications like the simulation of the construction process and serve as a base repository for facility managers to operate and maintain the building.

2.1 Manual

The manual approach for creating as-built drawings is inherently manual intensive and error prone. Workers on site use tape measures or hand-held laser range finders to measure critical distances and red-line them on drawings. In unusual cases these measurements might find their way back into electronic CAD drawings. Accuracy is limited by the manual nature of the data gathering. Technology has been harnessed to improve this approach by some solutions providers through the integration of a laser tracking system and a hand held computer to automatically record positional information in electronic models (e.g. BIM or CAD). The user uses a special pointer to indicate points to measure on installed construction elements [6] corresponding to elements selected in CAD using the handheld PC. Hardware setup of the laser tracker on a tripod is relatively quick including registration measurements against known installed features relative to a CAD model. As the process remains predominantly manual and user driven, the number of measurements possible remains low.

2.2 Video, Time Lapse Photography & Photography

Video, time lapse photography and photograph documentation of construction progress and activities are becoming more common in projects as the supporting technology has gone digital, and become more integrated and much cheaper to implement. These approaches are popular for big projects so stakeholders, the public or the owners, etc., can monitor progress over the web. Archives can be indexed by time and location, in the case of more than one camera, but they cannot provide actual spatial data on their own. If correlated with bills of materials, schedule information and reference locations or features in images it is possible to extrapolate some usually low quality dimensional data. Abeid et al. [10] integrated captured images with databases that contain schedule information to produce dynamic graphs showing planned versus actual schedules.

Though not yielding actual as-built documentation, the information is, by nature, up-to date and can be used to support the decision-making including planning and site meetings during construction. High quality digital pictures can show sufficient detail to serve as a reference for future facility modifications, repairs and inspections [13]. Other benefits shown include reductions in disputes and accidents, the possibility of remote real-time diagnostics, and enhanced communication between stakeholders regarding onsite activities.

Research in this area has looked at linking electronic copies of drawings, notes and sketches to imagery such as was done at Virginia Tech [24]. Their developed system builds on top of the computerized project schedule by electronically linking all drawings that are used in the project. As the construction process gets executed, the changes are redlined manually on the electronic copies of the drawings and stored.

Comparison of construction photographs and virtual reality (VR) images of construction has also been used to examine the difference between the actual situation in a job site and the 3D CAD design of the building [23], a form of gross visual inspection. However, in order to compare construction images to a VR model, the viewpoint and direction vector of both should be coincident as the report states that the “accuracy of objects for comparison highly depends on the correction of the deviation angle of camera in a horizontal plane and the 3D viewpoint of the construction photograph that has been presented”. Based on the authors’ experiences, it takes a fully trained person to map photographic images to the as-design models (or vice-versa in the case of augmented reality) and conduct the analysis. Manual mapping methods are time consuming and erroneous and current computerized approaches are very dependent on good equipment setup, calibration and use of robust algorithms to register and combine the model and real view. In [11], pairs of point correspondence between models and images are used to eliminate the scaling, location and orientation problems for augmented reality applications.

2.3 Photogrammetry

Photogrammetry techniques have long been used to assist in realising CAD and virtual models of existing structures for architectural purposes. In fact there is at least one journal, ISPRS Journal of Photogrammetry & Remote Sensing, devoted to photogrammetry techniques where numerous articles on applications in architecture can be found. Photogrammetry uses two or more images taken from different locations and basic triangulation principles to locate points in the images in 3D space. It should not be confused with 3D photography where fish eyed lenses and stitched photographs allow the user to look in any direction from one point as mentioned in [21] or 360º panoramic imagery described in [16].

Again, the fact that digital cameras with relatively high resolutions, decent lenses (necessary for acceptable accuracy) and large memory capacities are nearly commodity items today is a strong incentive to revisit the use of photogrammetry based approaches to realising as-built documentation. In fact good quality cameras are now being built into mass market cell phones and digital stereo cameras are not uncommon even if a little more expensive. In terms of hardware, cameras are cheaper, more assessable, more portable and faster for capturing on site data than any other technology other than a simple tape measure (which is cheap but not fast). What is required is a computer and special software to get useful geometric data from the pictures.

On the whole, it is still very difficult to get computers to recognise general objects in images except for structured scenes with severe limits on objects so humans remain an integral part of the photogrammetric path to as-built models. Thus most approaches focus on a semi-automated or human directed approach. Furthermore, photogrammetry approaches rely on good images so lighting is an issue unlike many laser scanning implementations (discussed later).

Some consulting companies [19] specialise in using these techniques to create accurate as-built documentation for complex projects, and they tend to used more sophisticated equipment like high end stereo cameras and place registration markers in the scene to improve the quality of the data they gather and the resultant models. They also will have significant expertise and software resources with which to process the data gathered and create the resulting models.

In essence, to extract spatial information using photogrammetry techniques requires knowledge of the camera locations and orientations (pose) for each picture and matching points in multiple photos of a feature to be measured. Given enough images and matching points it is possible to calculate where the cameras were. Software like *Microsoft Photosynth* [7] takes many images and automatically locates matching features to support determining the camera poses around a common 3D scene in the photos. With this information, Photosynth can place the images in the 3D space like billboards to give users the illusion of space. *Autodesk ImageModeler* [4] requires the user to manually identify matching features but gives you tools to build geometry directly from any measurements made. To then get geometric information from the pictures requires providing a scale based on a known length in the images and identification of feature points to be measured between in the images. Done this way the data yielded is not much more detailed than a series of manually acquired lengths or 3D locations that can be used to build or compare to CAD models. When using stereo cameras with known optical properties the results can be grids of depth information. Accurate measurements rely on accurate location of points in multiple images and thus the best results are achieved for edges and other distinguishable features and poor or no results are typical for surfaces, especially curved ones.

Research continues into improving the level of automation of identifying and matching important features. One older, but particularly interesting work, is the rather comprehensive effort made by Hirshberg and Streilein [22, 28] where the authors provided interpretive directions for the software in the form of pre-defined straight-edged profiles of features which they wish to have matched and measured in images from edge drawings or pre-processed semantic models of expected geometry found in the as designed CAD model. Their software iteratively matched the outlines to edges found in multiple images using edge-detection image processing techniques. Once the images were registered with each other the resultant geometry of 3D points, edges and loops was exported directly to CAD for comparison of as-built to as-designed.

In another sophisticated approach to automatically identifying construction objects from digital pictures, Brilakis [15] used photogrammetry to aid the inspection process by semi-automatically identifying where pictures are taken and what direction they are looking in relation to an existing CAD model and pulling up that part of the model for inspection comparison by the user. A GPS enabled digital camera is used to capture images which are then filtered by attributes and clustered to narrow isolate key construction features. These features are analysed using Content Based Image Retrieval (CBIR) techniques with matches being limited to objects expected in that part of the construction site based on the CAD model.

Given that the objective in this work is to identify and document installed services, the capabilities of the approaches above suggest that a nearly automated system should be possible to capture straight runs as the geometry of the objects being sought is well understood and known in advance. However, the user will probably have to provide further description about the nature of each service found as there is little or no difference between air supply and return ducts, hot and cold pipes, conduit for electrical or phone or network and different types of waste plumbing.

2.4 Laser

3D laser scanning (a.k.a. LADAR – Laser Distance And Ranging) is a newer approach than photogrammetry techniques. It requires much more expensive equipment in general, though prices continue to drop, and yields significantly higher levels of accuracy. The higher accuracy is often achieved through capturing much larger sets of data, typically clouds of 100's of thousands or millions of 3D points. Direct measurements and simple visualisation can be done directly from the un-processed data using the system supplier's software. Another advantage of laser scanning is that it is usually much less sensitive to ambient lighting conditions but the authors' own experience has shown that in some cases vegetative surfaces have been found to absorb the wavelength being used by the scanner. Unlike photogrammetry techniques laser scanners are good at getting dense measurements over even smooth surfaces.

One potential drawback of laser technology is that the operating field conditions of many construction sites, including extremes of temperature, humidity, and dirt, must be considered given the sensitivity of laser scanning equipment. Furthermore, current commercial options for post-processing are mostly manual or assisted manual and require powerful computers with lots of memory to handle the large datasets. The registration of multiple scans to a single coordinate system is usually a fairly quick though manually directed process, but generating models from the data is still intensively manual. The application specific exception is in using high-end software, like *Innovx RealityLinx* [9], which is designed to support rapid matching of parametric CAD models to user selected sections of scans of industrial piping installations as found in factories, refineries and chemical industries.

Given the immense number of sites of historical, religious or architectural interest, a large number of publications document investigations of laser scanning technologies to accurately capture their shape and colouration. The resultant models were used for virtual tourists, educational purposes, simulations and academic study. For example, Shih et al. [27] use laser scans to digitally preserve a historic temple in Taiwan but the models were made manually and for the most part only represented net shape and not semantically separate construction elements as would be necessary for machine reasoning applications. Arayici [12] describes in decent detail a process involving manual steps using *PolyWorks* [8] to convert a laser scan into a facetted model suitable for use in visualisations, and ultimately into BIM models. Arayici's approach semi-automates the process of extracting profiles for use in CAD model development by aligning the scan with an XYZ axis and then using scripts to project points near user defined planes onto planes to create the desired profiles.

For inspection applications during construction, *Autodesk Navisworks* [5] supports overlaying "as-built" models, including information derived from laser scans on "as-designed" models for visual comparison and analysis. The software includes a point/line based interference detection module to assist in performing clash tests against specified geometry to identify discrepancies. Figure 1 illustrates the results of the in-house scenario of an as-design model as shown on the left side of the figure against an as-built model generated from the captured cloud of points using the Faro laser scanner.

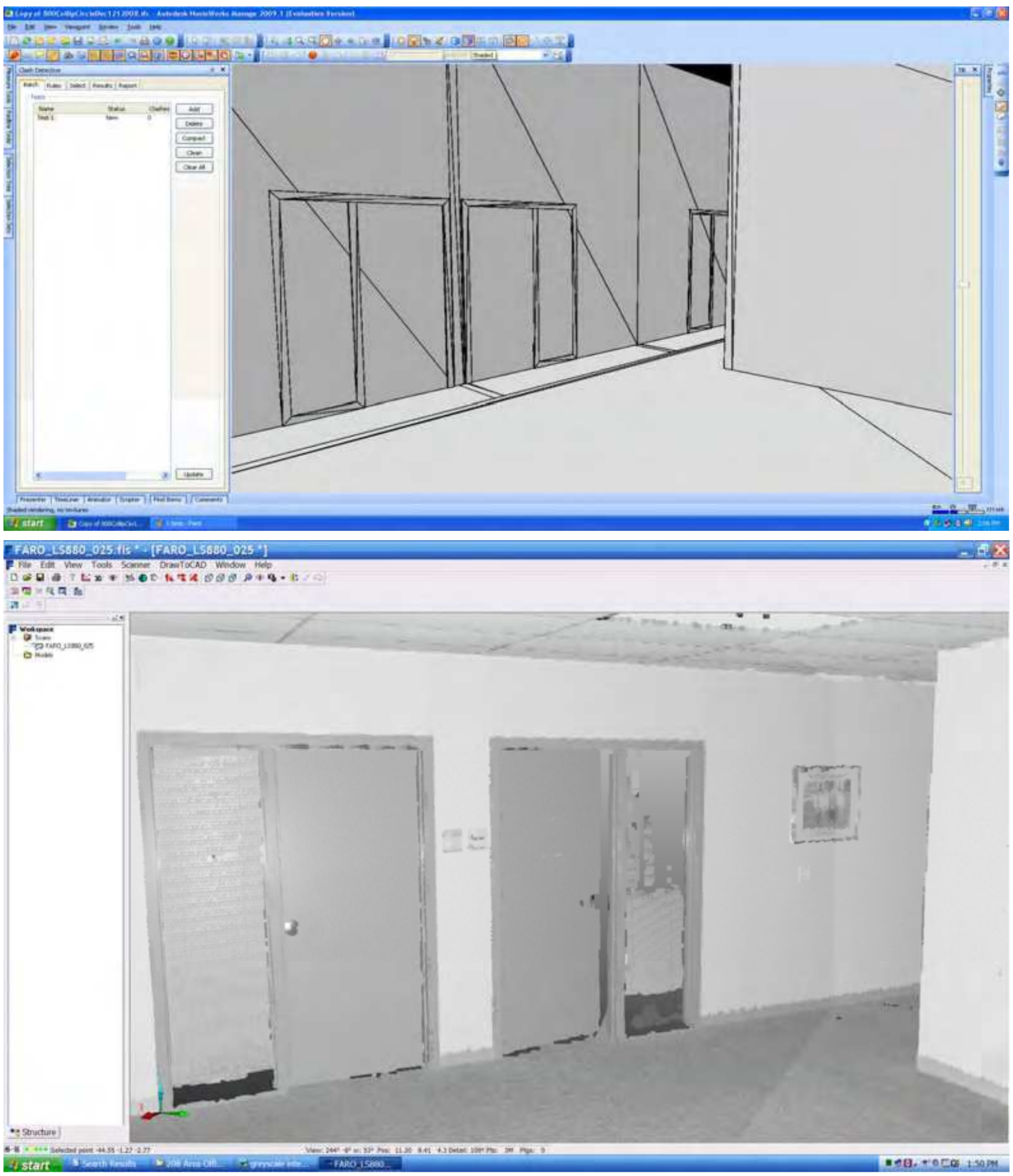

Figure 1 An example of as-designed (top) vs. as-built (bottom)

Bosche et al. [14] have placed significant effort on automatically "retrieving" 3D CAD models of objects found in scanned images, a significant road-block to automated inspection or contextual as-built documentation. The scanned data are aligned with facetted versions of the planned CAD models and then scanned surfaces are compared with those expected. The result is a difference map which can indicate how well as-built circumstances match the plans at a semantic or object level. This approach remains under development and is sensitive to magnitude of the discrepancy between planned and actual construction and transient objects like unused construction material or debris in the scans.

As with photogrammetry, the capital outlay and expertise required to own and efficiently operate laser scanners has traditionally relegated their use to consultant companies [29] or large firms.

One hybrid laser scanning and photogrammetric solution was investigated by El-Omari and Moselhi [18]. Their approach uses a few low resolution scans augmented by more numerous quick photos to allow more rapid gathering of data with still accurate reconstruction. The photos were “merged” manually with the point cloud data to fill in areas not scanned and allowing more accurate definition of boundaries of objects yielding more accurate geometric data. El-Omari and Moselhi plan to continue their work to integrate RFID, bar coding, laser scans and photos with portable computation to automate the reporting of progress on construction sites.

3. Observations and the Future

Except for specialised applications, of all the methods for gathering the raw data for creating as-built documentation, the authors find the simple camera to have the most future potential due to its low cost, portability, availability and rapidity of data capture. In fact, for simpler construction jobs, the quality of today’s digital images combined with the some correlated as-built documentation may prove to be sufficient to locate building services as required after construction. This would, however, require good photos be taken after each MEP element is installed with broadly identifiable features included in the images. If images are captured regularly, correlated with the designs, and made available immediately for planning or coordination sessions they could support effective construction management practices.

For more complicated jobs or installations or to update digital designs, sufficient information coming from fixed cameras, multiple photos or video data, combined with photogrammetric techniques should support creating as-built records of MEP element locations often within centimetres or better. If higher accuracies are needed then laser scans or other more advanced equipment may be required to gather the raw data. Unfortunately a significant bottleneck remains in having to manually updating existing CAD or BIM models with as-built dimensional information.

The authors see significant potential in a combination of photogrammetric software with CAD applications to support overlaying multiple camera views on 3D models for rapid visual identification of differences in design and implementation. Additional tools for the rapid re-alignment and positioning of components to match the photographed reality would greatly simplify recording as-built conditions in digital models. Further application of newer Content Based Image Retrieval (CBIR) technologies could then lead to automatic matching of as-built to as-designed components and ultimately to automatic updates of as-built models, subject to operator oversight. These goals should be realisable more quickly by narrowing the scope of automatic recognition to specific domains, like MEP for example. As mentioned earlier, some software like *Innovx RealityLinx* [9] and *Autodesk Navisworks* [5] are already taking steps towards these targets, however aligning as-built data with models remains an onerously manual task.

Though not the direct focus of this work, it is worth stating that if no electronic models exist, a common problem for many heritage and even modern facilities, significantly more human effort is required to build models from scratch based on human knowledge of the individual components and the gathered dimensional data. For example, one of the authors used a *FARO* laser scanner [2] in 2006 to create as-built models for a manufacturing facility where no CAD data existed. In total the process **took about 3 person months** to complete. The following outlines the manual steps involved:

65 spherical and paper targets were strategically placed around the environment to facilitate registration of the 37 scans taken over a period of two days. As each scan was completed, the raw range data was sent to a PC for alignment and registration. With two skilled operators working in parallel, the scanner and PC were kept in constant utilization. In total, over 1 billion data points of X, Y, Z, location and R, G, B intensity values were captured. The size of the data set itself caused the computational time for many of the raw range data analysis and manipulation operations to be measured in minutes when processing with *FARO Scene* [1] software. Also only three or four scans could be loaded simultaneously before hitting 32-bit Windows maximum limit of 2GB of memory per application. The practical work around required manual swapping in and out of adjacent scan sets and repeating the registration process with a second pass through all the scans to align adjacent scans not aligned during the first pass. CAD models were then built manually from extracted dimensional data from the entire scan data set using dimensions directly measured using *FARO Scene* or through tracing in CAD imported tomography projections of a slice of data onto a plane (Figure 2).

To create visually realistic models (Figure 3a), *3ds max* [3] was used to load the CAD models and add textures based on pictures taken in the manufacturing facilities. The final result was CAD (Figure 3b) and 3d models suitable for CAD design or advanced visualisation applications like the ability to create still images, animated videos, and even environments for self-directed navigation through the space.

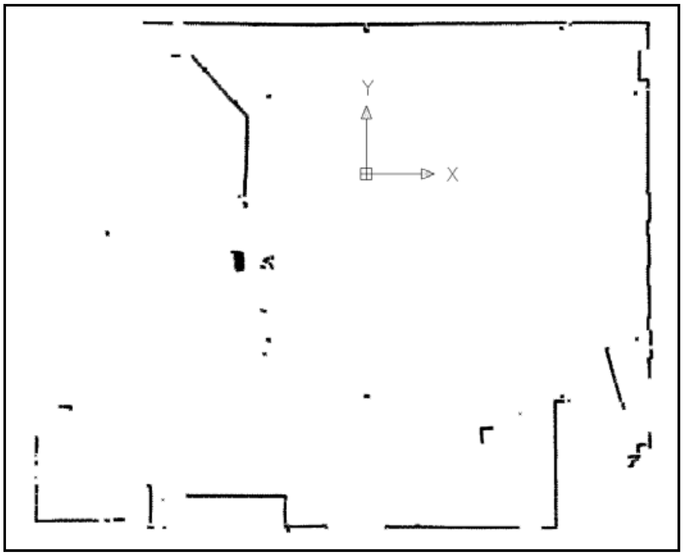

Figure 2 An example of a horizontal (plan-view) tomography based profile as viewed in AutoCAD.

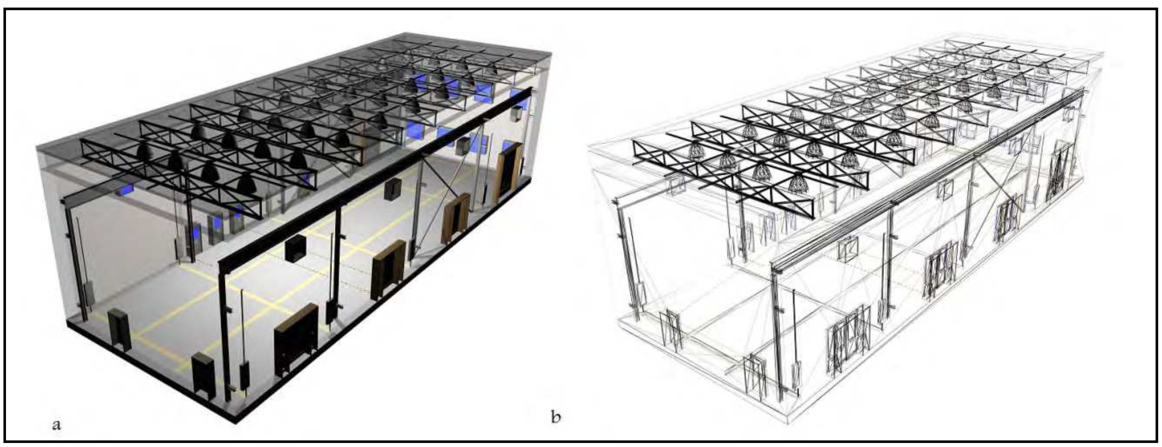

Figure 3 a) Example of a visual model of a high-bay facility based on CAD model b) Direct visualisation of geometry from a CAD model.

In terms of improving building models from raw data, it should be noted that although only 3 years have passed, new computers and operating systems should improve the speed of computations and number of scans that can be registered in one pass. Still, the identification of targets in each scan remains a manual process (for photogrammetry and laser scans) but new RFID or other technologies could be used to allow the software to identify targets and control the alignment process freeing the operator for other tasks. Such jobs could be left to run overnight or over a weekend as required once all the scan data was captured. However, it is creating the model from the gathered data that remains the longest and most manual task. The better superposition of multiple full colour images into CAD environments, as mentioned above, could greatly ease adding and aligning library components to realise rapid model development. The further future would hopefully include more robust recognition of objects as-built, potentially based on tagged construction materials (e.g. RFID) that can be electronically queried for their identities or in the case of older constructions, more advanced object recognition technologies able to identify common elements from images.

4. Conclusion

The authors have presented an overview of traditional and newer technologies used in the creation of as-built documentation with a bias on their application to MEP services. Though robust solutions do exist they remain manually intensive and often require expensive equipment and trained personnel. However, new software technologies (i.e. image processing and image registration) and cheap digital cameras show significant promise for the creation of new tools that could greatly ease the manual work required to keep as-built documentation up to date and support on-going construction. In the further future as image processing and object recognition technologies improve there is hope for nearly fully automated as-built documentation for specific construction domains.

Although these technological approaches are still in their infancy they are rapidly becoming more practical to realise as the construction site and project documentation goes electronic. The solution does not lie in one technology but rather the integration of these technologies into simple tools for the industry to use.

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