1.3 NIST Construction Automation Initiative

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Before we get started, let me introduce a few key people who have helped to organize this workshop. I would like to thank Ken Goodwin from the Manufacturing Engineering Laboratory (MEL), Kent Reed from the Building and Fire Research Lab (BFRL), and Jim Albus and Nick Dagalakis, also from MEL.

One of the reasons that we are here is to see where we might be able to go with future construction technologies. I would like to open with the thought that "It's already been done." And I have a video to prove it. [Brief clip from the 1984 movie Runaway, staring Tom Selleck, showing industrial robots constructing a high rise steel frame building].

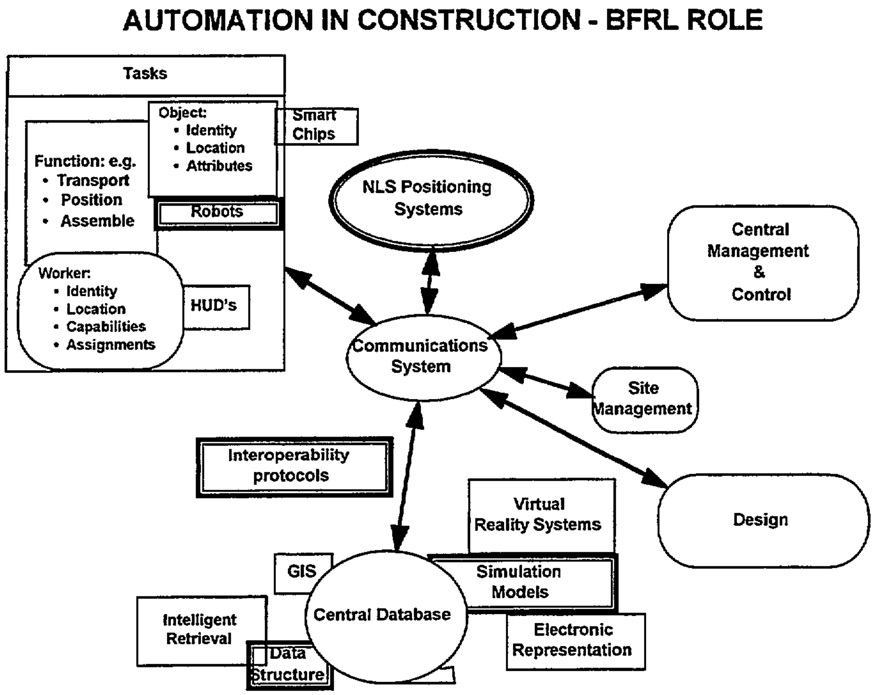
It has been said that Hollywood is always twenty years ahead of reality. The interesting aspect is that this movie was produced 11 years ago. Which means we only have 9 more years, so we had better get moving.

There are many visions that people have had over the years concerning how we might get to that future where the construction process is automated. Certainly, there is an impetus to eliminate dangerous tasks in an arguably risky industry. This is so well known that the Japanese have a saying which captures the essence of the construction workplace: "Kitanai, Kiken, Kitsui" (Dirty, Dangerous, and Difficult). This has secondary ramifications in which the above perception leads to reduced appeal to the workforce to pursue this type of work, which thereby exacerbates skilled laborer shortages and reduced productivity. These latter aspects have motivated such large construction conglomerates as Shimizu and Obayashi to invest heavily in the automation of those procedures deemed kitanai, kiken, and kitsui.

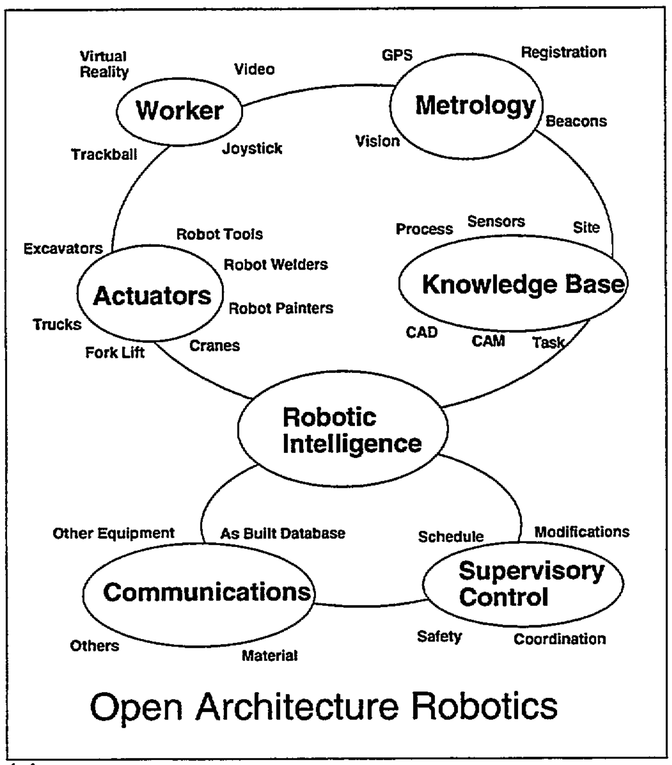
Safety and undesirability aspects aside, construction is an industry which represents 13% of the U.S. GDP and there is significant pressure to achieve greater speed and efficiency in order to remain competitive. Can these disparate vantage points be reconciled through automation?

What we seek, ultimately, are ways in which we can automate various construction processes that are presently manually intensive or dangerous. Equally important, we seek the means to provide up-to-date information to all project participants -- including owners, architects, designers, fabricators, contractors, and workers -- so that delays can be minimized.

People have tried for several years now to come up with possible "architectures" for how we might do this and they all seem to revolve around various common concepts. These include things like metrology at the job site, how you communicate certain pieces of information back and forth, the use of common global databases and processing, and the various ways in which you make use of that information to automate various facets of construction practice.



Figures 1.3.1 & 1.3.2: Two examples of proposed architectures for construction automation



If you organize these topics based on the priority of information you will find that metrology is the common precursor for any form of automation. Metrology in this sense can be loosely interpreted as surveying, but in fact it goes well beyond that. In an automated environment it involves not only the pre-established location of a few control points that establish property boundaries and grade lines, but also the ever changing positions of everything from terrain profile grids, to the location of components and machines in real-time.

Once you have position measurements the big problem is how make use of the data. Presently, most data collected at a jobsite is either manually transcribed or placed in data loggers for subsequent use at the construction shed and back at the main engineering office. Obviously there are time delays between there and the design office. So we are looking at the idea of wireless communications for data transfer.

Construction Automation & Robotics Initiative

Research Program Topics:

- **Sensors for Real-Time Construction Site Metrology**
- **Wide Band Telemetry and Data Acquisition**
- **Virtual Site Simulation and Object Representation Standards**
- **Person-in-Loop Systems**
- **Construction Robotics**

Once you get that information, then you have to figure out how to process it. What format should it be in? Who should be able to read it? How should new data be processed? At what update rate? Which processes take priority? Some database interchange standards are already being developed: STEP, ISO, IGES and RTCM to name a few. Many other standards are still needed.

Virtual modeling -- permitting three dimensional computer representations at remote access workstations to visually depict the status at the real jobsite -- is a new way of representing the vast data that would be generated at an automated construction site. In this concept, data gathered at the site could be used, for example, to establish the location of an installed beam or column. The virtual model, given these critical keypoints, creates a photorealistic image of the element within the context of a 3D computer model of the construction site, and displays the beam or column at the location just measured in the field. The same techniques can be used to relay the position, attitude, and articulations of construction machinery, as well as many other defining attributes including the health of the machine. Standards are needed for how we represent these packets of incoming data so that they can handle the wide variety of categories of measurable data.

Once we have a global database established we would like to return real-time information to various users in a useful format. The obvious immediate users are engineers at the design office who could accept instantaneous representations of the as-built facility in the form of CAD drawings. Such as-built data would also be of substantial valuable to project managers. In our view, however, this is a myopic assessment of the potential possibilities. The real benefits will be gained when the information is turned full circle and provided on demand to a variety of users at the job site, including laborers and machine operators.

The ultimate expression, of course, is semi-intelligent or semi-automated processes at the construction site in which humans and machines complement each others' talents in a manner which is more productive than would be possible using either alone. There are many different beliefs, and predjudices concerning robotics and whether there is a place for this at the construction site. We expect to address this topic today and hopefully dispel some of the myths and clarify what is realistically achievable.

As many of you are aware NIST has proposed an initiative in its FY96 budget in construction automation. Six million dollars per year has been budgeted; what actually happens remains for the Senate to decide. But of the six million, two will be going to Building Systems Automation, that is monitoring systems involved with measuring and predicting the lifecycle process of the building. The remaining four million will go to what we call Process Automation. That is taking the construction of a building from a green site all the way through delivery to the owner and all of the information transfer that goes on in that process.

We've divided process automation into five topics. The one that is receiving early attention is site metrology. This program has been active since last October, and later this morning we'll discuss the kinds of data that have been acquired and where we are heading with this work.

What types of information are of interest from a construction site? We believe that, ultimately, the level of interest will include not only the position of every component, but also the locations of vehicles, and the status of their independent articulations -- for example the state of all of the various moving parts of those vehicles that would be of importantance in assessing the potential for a collision. In other words, if you wanted to use semi-automated vehicles on the construction site, what is the minimum information you need, and at what update rate should this information be provided, to insure the reliability of safety algorithms?

In addition to this, it's my contention that we're also going to have to know where the people are. It may be that we, as a society, are not yet ready for worker I.D. tags, but at least we want to know where people are so that somebody doesn't run over them with a big piece of machinery when they are not within the line of sight of the operator. This is not an idle concern: there was an accident in Pittsburgh about a half year ago in which a surveying inspector was buried one night while an excavating company was working on a new shopping mall. The fellow happened to be behind a large pile of dirt when a big dozer approached from the other side, unaware of his presence.

Real-Time Site Metrology

Technical Goal:

- **Position to 10mm in 3D**
- **Acquisition Time < 1s**
- **Penetrate 50m through Structures**
- **Remote PC interface for Data Uplink**

Knowing where people and vehicles are at all times means tracking in real time. What we mean by "real time" is relative. You may not need to update your knowledge instant by instant for everything at a construction site; only those for which things are changing rapidly. For example if you are placing rolled steel sections with a crane (which might be semi-automated) you want to know on a fairly regular basis what new components have been put in place, and where they are located.

In addition to position, there are other details that might be of interest. For example, you may want to verify the properties of a column or beam and where it was produced, its yield strength etc. This leads to the idea of bar code coding or smart chips which store this type of information local to each component. In addition, it may be desirable to have such information storage tags be of a read-write nature, so that critical time stamps (e.g. date of erection) might be added.

These ID tags would be assigned to all manufactured construction components including things like precast beams, columns and slabs, wide flange steel sections, rebar, wall panels etc. In addition, the orientation of a construction element is of critical importance, which means you have to acquire a certain number of additional key points. For example, the 3D locations of a minimum of three orthogonal points are required to establish spatial positioning of a rigid-body item. How you acquire such data is an interesting dilema which we will talk about in more detail later.

In order to be practical we need to acquire component position to within ten millimeters in three dimensions, and acquire it in less than a second. By way of comparison, you can get one millimeter accuracy over a hundred meter baseline with existing total survey stations equipped with electronic distancing. But there is more. A good metrology system in the automated environment must do three things: a) it must be capable of measuring the three dimensional position and attitude of any component to a reasonable degree of accuracy (which varies depending on the circumstances); b) it must acquire these data fairly rapidly, in some cases with an update rate as fast as 10 Hz; and finally, c) it must be capable of making reliable measurements anywhere on site. Items b) and c) rule out the use of "total stations", since these are designed for point-to-point static precision surveying.

Where you have line-of-sight path, as for example in green field earth moving projects, there are two new, and rapidly evolving technologies -- GPS and fanning laser systems -- that will see use on construction sites within the next few years. We'll be talking a little bit about real-time kinematic differential GPS (or RTK) and what you can actually do with that and finally a few thoughts on pseudolites and where those might see utility at a construction site.

Real-Time Site Metrology

Promising New Technologies:

- **NLS Technologies (SAR based)**
- **GPS Pseudo-lite Emulators**
- **Sub-Centimeter Kinematic GPS**

However, the rub is that neither GPS nor any laser or infrared based distancing system will work when obstructed by even the thinnest of objects. As everyone knows, construction sites are highly unstructured environments -- in contrast with, for example, an automated factory -- and clutter is the norm. You cannot expect to use line-of-sight measurement capabilities for general purpose tracking once structural elements have been erected. But it would be awfully nice -- and simplifying -- if it were somehow possible to measure distances inside a building relative to an exterior benchmark despite the presence of intervening walls. We have a rather unique program underway at NIST to address this topic and will be showing some of the preliminary results later this morning.

Thus far we have discussed measurement systems. <u>But the data for a single position reading are of little value unless it is integrated into an ever changing representation of the complete site</u>. In many respects, individual position measurements can be viewed as independent sensors. In a laboratory experiment it would be possible to connect each position sensor to a central computer via coax wiring and a change in any sensor would be read, nearly instantaneously, by the computer. In this vision a position sensor would be attached to every component and machine at a construction site. However, unlike a laboratory experiment, there can be no wires running around a construction site for a host of practical and reliability reasons. Thus, the problem is how to uplink , via wireless technology, several hundreds of channels of data out of a construction site.

The issues that are of concern are security, fidelity, and bandwidth. Security means that only the construction company, or authorized subcontractors, have access to the data. Fidelity means that the signal to noise ratio is high, despite likely interference in an urban environment, where cell phones, TV stations, and other construction sites will contribute to radio interference. Bandwidth refers to the available frequency spectrum through which data can be transmitted; the wider the bandwidth the greater the potential data transmission rate and the more items that can be tracked in real-time.

The destination for all of the data to be transmitted from the construction site -- and subsequently uplinked via the internet or dedicated fiber optic line -- is a global data management system. The protocol and capabilities of such a global database have seen great attention over

Construction Site Telemetry

Key Issues:

- **Interfacing hundreds of on site positioning systems with global job database**
- **Maximizing real time data reliability (inter-city construction will involve many transmitters at competing nearby jobsites)**
- **Federal Communications law**
- **Data security**
- **Cost**

Virtual Site Simulation

Technical Goals:

- **Develop standard real-time virtual simulation generator tools for construction site management.**
- **Develop standard kinematic graphical representations for construction site objects and vehicles.**
- **Develop modular real-time software to link site data to kinematic response of virtual objects.**
- **Develop Standard Re-configurable machine simulator/teleop training Station.**

the last decade. This morning you will hear from Ernie Kent of the Manufacturing Engineering Laboratory, Kent Reed, from BFRL, and from Mike Simms with NASA, on how we might be able to go about handling jobsite data once we acquire it. Kent Reed will be discussing some of the issues related to standard formatting of the data so that it can readily be used by different hardware and software systems. Given sufficient information, it is possible to create a real time computer-rendered image of what the actual site looks like. This involves the subject of virtual modeling, which will be discussed by Ernie and Mike.

NIST is presently developing a dedicated real time virtual simulation testbed for construction site management that will allow data interchange formats to be evaluated with real construction equipment in the loop. Right now there is no off-shelf software out there that will do this type of task and the hardware must be assembled as a laboratory prototype system. There are many barriers to the practical implementation and common acceptance of such a system. For example, while it is possible to define a machine or component in any number of CAD programs right now, standard formats for graphical representation of construction site objects and vehicles are nonexistant, as is software which makes it easy for for those items to be incorporated into any project planner.

Given component and machinery representation standards we envision a typical manufacturer of wide flange steel sections, for example, having a standard CD ROM containing section details, properties, and ID tags that describe all the manufacturer's products. Likewise, designers and manufacturers of construction equipment might deliver their machinery along with a compatible software representation of the machine that can be used by a generic project planner. The power of such standards lies in the ability to easily and intuitively specify generic standard components and/or machine tasks at the earliest stages of project design. These digital specifications would then carry on throughout the duration of the project and permit ease of tracking as well as progress assessment. One of the things we see as a very useful generic tool within the next ten years is a standard reconfigurable machine simulator which would primarily see use in training and process evaluation, but would also double for teleoperative control in hazardous jobsites. This sounds far off, but there are a large number of common jobsite tasks done today where a high fidelity teleop station would not only allow greater safety, but would actually improve productivity by permitting interactive adjustment of the point of view. The most obvious of these is the operation of a high rise tower crane. The

Person-in-Loop Systems

- **Data Needs at the Construction Site**
  - **Numeric**
  - **Graphics (e.g. blueprints, terrain profile)**
  - **Audio**
- **Human Factors Engineering**
  - **How much data to be displayed?**
  - **To whom?**
  - **How to display it?**
  - **How to access it?**
  - **How to log it?**

approach to development would largely involve integrating military flight simulator capability with a jobsite global database.

As I indicated earlier, we believe that the early payoff in construction automation will be achieved by providing useful processed data, on demand, to foremen, workers, and equipment operators at the construction site. Thus, we are looking at practical means for getting information back to the construction site. We have identified several early candidates. One is the idea that everyone that works on the site would have a very lightweight, hardhat mounted display system that either upon voice activation or some other simple queuing system will give them information that they need to do their job. One example that comes instantly to mind is a component location capability which directs the user to the current whereabouts of the desired part. The technology is usually referred to as a Head-Up Display (HUD) or Helmet Mounted Display (HMD) and we actually have some hardware here that will be demonstrated by Ron Levondowski from Honeywell. These are being developed for the military right now. The analogy to the construction industry is readily apparent.

Person-in-Loop Systems

Technical Goals:

- **Develop Helmet-Mounted (HMD)"Database Interrogator": direct info to average construction worker.**
- **Develop HMDs and/or projection HUDs for Graphics-Based Feedback for operator-controlled construction equipment.**

We also want to provide on-demand information to vehicle operators. In the context of construction operations these would include machine specific feedback for everything from forklifts to dozers, backhoes, and cranes.

This now leads into the issue of human factors design. For example, how do you display the information, what is the least amount of information you really need, what tasks will you allow to be semi-automated etc.. The engineering questions largely reduce to the nature and amount of data that will be transmitted to the vehicle operator. The human factors side says, "We can give you all the data you want right now, but can you use it effectively? There are a lot of people who have experimented with head-up displays before and you know that if you have a constant red blinking light out there that's trying to tell you that the system has a fault, people will simply block it out of their mind if the machine continues to work and whatever fault was detected is not affecting the equipment. Those are some factors we must eventually deal with in terms of making information effective when it is delivered to the job site.

Finally, I would like to say a few words concerning construction robotics. This involves the idea of either fully

Construction Robotics:

What is Futuristic ?
What is Achievable?

- **Turning loose a 1000 horsepower machine or a 50 ton crane on a construction site without human supervision is <u>not</u> likely in the foreseeable future.**
- **More likely: full time operator does the set-up, fixturing, initialization, and choice of process to be performed.**

Construction Robotics:
Guiding Philosophy

- **Let the OPERATOR do what is easy and natural for a human.**
- **Let the COMPUTER do what is easy and natural for the computer.**
- **Machine-Operator TEAM may be 5-10 times more productive than conventional methods.**

autonomous or semi-autonomous operations at a construction site. You saw a little bit of what that might look like in the Hollywood film. The real question is, "what is reality -- what is really achievable." Jim Albus was asked this question a while back and he came up with what I thought was a rather memorable quote: "turning loose a thousand horsepower machine or a fifty ton crane on a construction site is not likely within the foreseeable future without human supervision."

Construction Robotics

Technical Goals:

- **Down select of most desirable construction task candidates for automation**
- **Initial Demonstration Project in semi-automated robot operations (on site setup by construction personnel; autonomous task execution by the robot)**

My suspicion is that the American Trial Lawyers Association would also advise you that this would be a prudent course of action. The hybrid scenario involves the operator doing the task set up for a software reconfigurable machine that can do several jobs. The idea is to let the operator do what is easy and natural for a human and let the computer do what is easy and natural -- repetitive, precisely repeated tasks without fatigue -- for a computer.

What we're hoping is that the combination will be much more efficient and productive than either man or machine. At NIST, we presently have no projected budget under this topic. The reason is that we feel these are going to be applications specific. Our intent is to focus on the common underpinning technology first, and in the meantime develop a prioritized implementation list where semi-autonomous tasks might yield high early payback.