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GLOBAL INTEGRATION OF CONSTRUCTION AUTOMATION AND ROBOTICS

Derek Seward (D.Seward@lancaster.ac.uk)
Stephen Quayle
Lancaster University, Department of Engineering
Norman Mure
Jason Scott
Stent Foundations Limited

Construction automation and robotics devices need to be fully integrated with the company IT infrastructure if they are to be of real value. Object technology provides the most effective means of achieving this, but an industry-wide protocol must be agreed. Two attempts at achieving this, the STEP and IAI initiatives are reviewed. Two case studies are examined – the LUCIE robot excavator and the Stent automated piling rig. Problems in trying to comply with STEP are described.

1 INTRODUCTION

Global integration concerns the means of integrating robotic systems into the business process of their owner. Just as in manufacturing, robots and automated plant only become advantageous when properly integrated into an appropriate IT infrastructure which links design to manufacture. This is particularly the case with construction robots as the one-off nature of many tasks means that manual programming of individual robots would be uneconomic. Thus a CAD/CAM link for construction robots is required. A CAD/CAM link implies the transmission of product data between the various phases of the development life-cycle. This is made more problematic in construction, compared to manufacturing, because of the greater number of organisations involved. Architects, structural engineers, heating and ventilating engineers, quantity surveyors, main contractors and various specialist sub-contractors are all commonly involved. This means that a universally agreed format is required for data transfer. Two attempts to achieve this are STEP and IAI. These will be briefly discussed below.

In addition to programming information being transmitted from the office to the robot, global integration also implies that site performance records are communicated back from the robot to the office. The provision of on-board computing power and mobile phone technology makes two-way communication both easy and economic. In general communication may be at fixed times throughout the day, event triggered (such as on completion of a particular task) or on demand.

2 STEP

STEP is the popular name for the Standard for the Exchange of Product Model Data or more formally *ISO10303 Industrial automation systems - Product data representation and exchange*. Work started on the standard in 1984 and, after much international investment and research, an initial release of the first twelve parts occurred in 1994. There is no widespread industrial use as yet, but the continued development of software support tools and cheap computer hardware may encourage its adoption. The standard is highly complex, laden with jargon and acronyms, and the eventual number of parts is likely to exceed 1,000 [5] and take up several feet of shelf space [1].

A STEP model provides product information (i.e. what it is) but **not** implementation information (i.e. how it is to be exchanged or used). This demarcation is deliberate in order to preserve the universality of exchange between different applications and computer systems. (In terms of object-oriented development this is equivalent to saying that STEP models have *attributes* but no *operations.*)

STEP documents are divided into four main classes:

- *Description methods* (Nos. 10-19) - These parts describe various forms of the EXPRESS textual specification language [10] which underpins all STEP models. Formal specification in EXPRESS enables a model description to be unambiguously read by both humans and computers. EXPRESS-G is a graphical representational form.

- *Implementation methods* (Nos. 20-29) - These parts describe the formats for storing and exchanging data between applications and databases as well as the relationships to specific programming languages such as C++ and FORTRAN.
- *Integrated resources* (Nos. 40 -200) - These parts contain conceptual data models that are relevant across a wide range of different products. Examples of such models are geometric shapes, visual presentations and engineering drawings. Of relevance to construction robots is the *Building Construction Core Model* that sets out a formal structure for the relationships between the different parts of a building.
- *Application protocols* (Nos. 200 299) - These define specific EXPRESS data models for particular industries. Individual sets of documents will therefore be prepared for say the shipbuilding, automobile and construction industries. These documents are prepared by teams of domain experts and data modellers who start by deriving detailed process/activity models for the industry concerned. A detailed understanding of the processes is required to derive the key information that must be encapsulated within the product model.

Other parts of the standard deal with overall philosophy and conformance testing. A STEP software tool producer needs to be familiar with most of the early parts of the standard, whereas an end-user should only need to refer to the relevant Application Protocol (AP).

An interesting example of the use of STEP to facilitate construction automation came out of the European RoadRobot project [4].

3 IAI

The *International Alliance for Interoperability* (IAI) is based in the construction industry and includes CAD vendors such as Autodesk [2]. It was set up in 1995, partly as a result of frustration with the slow progress of STEP, but it has aligned itself with the STEP approach and adopts much of the technology. It has set ambitious targets for the creation of *Industry Foundation Classes* (IFCs), which is the IAI term for the STEP Application protocols. IAI claims to be commercially driven as opposed to STEP's research driven approach. Work to date has concentrated on the production of *usage scenarios*, which are then converted to more formal *process diagrams*. These process diagrams provide the basis for the creation of *object classes*, which, as in STEP, are represented in EXPRESS.

The effort has been concentrated in the domains of architecture, heating and ventilating engineering, construction management and facilities management. It is a measure of the size of the task that only a few sub-processes in each of these domains have been considered. None of the work is, as yet, useful for the self-programming of the construction robots considered here.

4 CASE STUDY 1 - THE LUCIE EXCAVATOR

LUCIE, the **L**ancaster **U**niversity **C**omputerised **I**ntelligent **E**xcavator (figure 1) is fitted with satellite GPS guidance, and onboard PC104 computers control the vehicle tracks to provide a positioning accuracy of 2-3 cm. This is adequate for most site

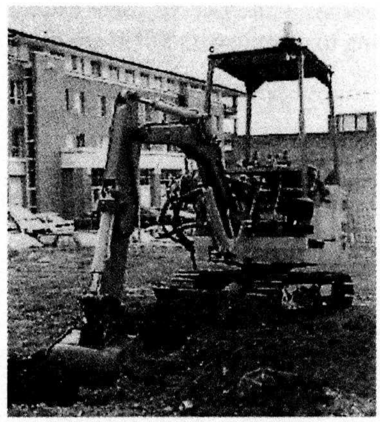

Figure 1
LUCIE excavator

excavation. The integration of a robotic excavator can be considered to be analogous to the interface between a computer and a pen plotter. With a plotter, a software *driver* is required to convert a graphical computer image into the commands to move the pen. Likewise with LUCIE, CAD images of the excavation task must be converted into commands for movement of the excavator.

Two approaches have been considered:

1. Interfacing to existing CAD packages provides a rapid route for early implementation. Several current computer drainage design packages produce manhole schedules that consist of manhole co-ordinates together with the invert level of all connecting pipes (i.e. the ordnance datum level of the inside of the bottom surface of the pipe). As pipes generally run in straight lines between manholes, this schedule contains all the information that LUCIE requires to dig the drainage trenches. However the order in which trenches are constructed is also important. The excavator must not dig itself into a corner from which it cannot escape without crossing, and hence damaging, earlier work. Thus an excavation planner is required to process the

manhole schedule and produce an ordered task list. A simple interpreter is required to process the output file from the different packages to get it in the same format for further processing.

2. Other excavation tasks are not so easy. For example a normal building foundation CAD drawing contains only lines which contain no semantics. It would thus be impossible to derive the excavation information from such a drawing. CAD packages such as AutoCAD allow *attributes* to be associated with *blocks*. Such attributes may include specific data such as the depth and width of a foundation, and hence the required excavation information could be extracted, however this approach is not ideal. The drawing production would be hindered, attributes can be changed easily, and no industry standard exists for the way that attribute data is defined. A better approach for the long-term is a fully object-oriented one, where a foundation has a universally agreed object model that contains all the necessary attributes. The STEP and IAI initiatives, described above should eventually deliver this goal.

As before, an excavation planner and scheduler is required to determine the optimum route to be followed by the vehicle. This is far from trivial and figure 2 shows the route for a simple two-bay strip foundation, based on interviews with experienced excavator operators.

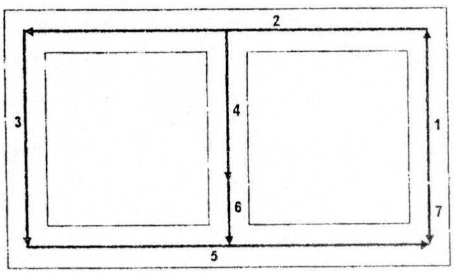

Figure 2
Excavation route

5 CASE STUDY 2 - THE STENT PILING RIG

A Stent piling rig has also been fitted with satellite GPS positioning, although this is principally as a navigation aid to the driver.

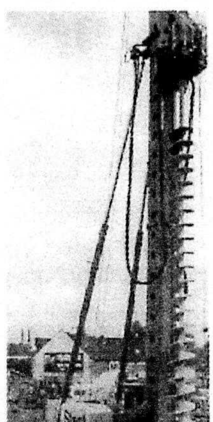

Figure 3
CFA piling rig

A typical continuous flight auger (CFA) rig is shown if figure 3. Global integration was regarded as an important requirement of the project from the outset. The decision had previously been made to adopt an object-oriented database known as *Object Store* [6] as a core data repository at the heart of the business process. This enables a two-way flow of data between the o-o database and actual site activity. Design information is issued for implementation on site, and logged site data is fed back for analysis and recording.

The external 'upstream' documents that inform the process are a specification, a site investigation and drawings of the proposed project. The 'downstream' documents are as-built records, and in addition current practice requires an increasing amount of site-logged sensor data that is used for quality validation of the product.

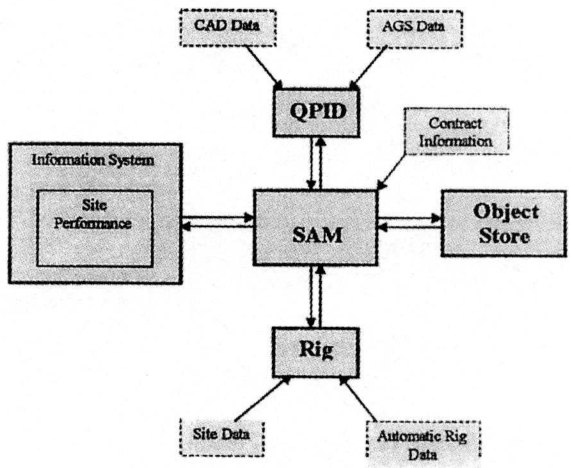

Figure 4
Software Architecture

A suite of software tools is currently under development to assist with the management of processes and the manipulation of data. These include SAM (Stent Applications Manager), which is a high level user interface used for all transactions with the O-O data base, and QPID (Quick Pile Design) which is a technical module for processing site investigation and CAD data, producing pile designs and preparing job instructions for the semi-automated piling rigs. The relationship between the software tools is shown in Figure 4. QPID is used to design each pile individually, create a table of results, export results to the o-o database for estimating and the pile co-ordinates to the piling rig for Autopositioning. Further information is contained in [8].

The piling rig contains a hardened PC (figure 5) which is connected, via a programmable logic controller (PLC), to sensors which measure auger torque, depth and rotation and concrete

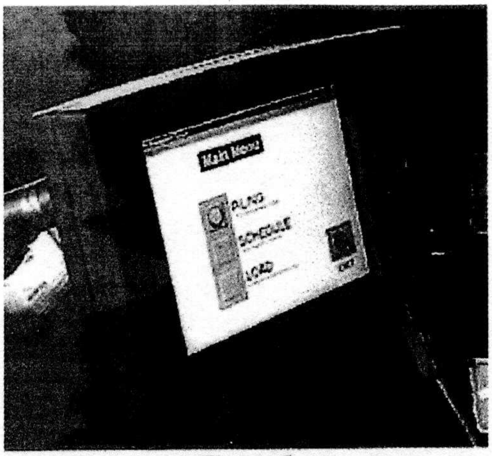

Figure 5
Driver display

pressure and flow. It is also equipped with a GSM modem for transferring data back to head-office at the end of the day. The driver communicates with the PC via a small, high-contrast, colour, LCD VGA display mounted in the cab, as shown in figure 2. The user interface has been written in Delphi [3] and is designed to minimise the amount of input required from the driver. All system functions can be controlled using the seven buttons built into the display.

Initially it was hoped to follow the STEP approach, and that an existing data model could be utilised with some additional objects added for Stent's personal requirements. After research into both STEP and IAI initiatives it became apparent that no such model existed in the detail required by Stent, and that one would need to be created from scratch. It was hoped that the model could be developed utilising higher level STEP objects which did exist, however these had not been considered in previous Stent work, and hence after some initial investigation were ignored.

Once it had been decided that a new model was required the main dilemma was how to arrange the model to cope with the different types of piling undertaken in the construct foundation sub-process. The equipment, techniques, and records used in the construction of, say, a driven pile are very different to those used for a CFA pile.

It was thought that individual models would need to be developed for each technique, and hence the specific area for data modelling was identified as CFA piling (although keeping the overall scope in mind). This was mainly due to limiting time constraints, and the fact that a CFA rig was available with full instrumentation.

After consultation with various experts from within and external to Stent, object models have been derived which are based on several viewpoints as shown in table 1. From this it was apparent that several layers of access were necessary for security and data integrity, hence the model developed should reflect this.

After much iteration a generic model was developed with attributes such as pile length and load, and aggregated objects such as 'PileConstructionLog' This object is then extended with sub-classes to define the different methods of construction. A further aggregated object defines the materials used in the pile construction. Each pile is given a unique reference number which remains

Internal to Stent	External to Stent
QPID package	Client/customers
Designers	Consultants
Project Engineers	Other Contractors
Foremen	
Rig Drivers	

Table 1
Viewpoints for models

with the pile throughout its life. The process was kept as close as possible to the STEP approach with ST-Developer [9] being used to compile Express descriptions and convert them into EXPRESS-G diagrams and appropriate C++ code. An EXPRESS-G diagram for a pile construction log is shown in figure 6.

Stent, in common with other piling contractors require a high level of detail on construction performance, hence the CFA construction log has aggregated-classes of boring log and extraction log. These contain precise details of machine performance over the construction of the pile and are automatically generated by the rig instrumentation. It is hoped to use this data in future research to design piles on-the-fly.

It was agreed that the work should align itself as closely as possible with international STEP and IAI standards. The perceived advantages of this were:

1. The adoption of a well developed data modelling process.
2. The availability of independent development tools.
3. The ability to adopt existing data models
4. The opportunity to make a contribution to the international effort.
5. Possible future interoperability with a 'Single Building Model' and specialist pile design packages.

It is felt, however, that these advantages have largely not been realised for the following reasons:

a) Although familiar with modern o-o concepts, the process of obtaining compliance with the standards was found to be daunting. The sheer volume of documentation and apparent complexity of the process was overwhelming.

Some valuable guidance is available [1] but the impression gained is that the steepness of the learning curve outweighs the benefits to be gained.

e) Having been forced to develop pertinent data models it is not clear what the procedure is for publishing these, and possibly having them considered for adoption within the standards.

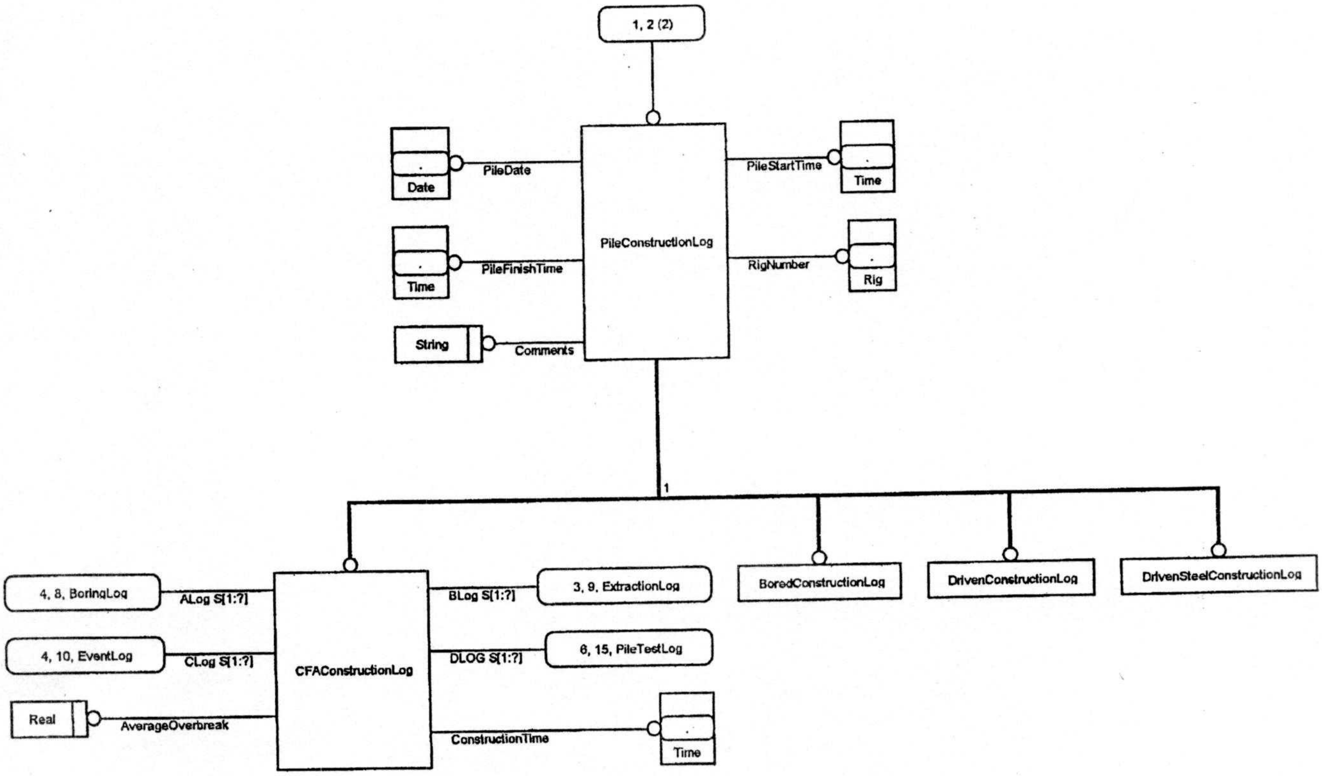

Figure 6
EXPRESS-G representation of PileConstructionLog object

b) The presence of the two organisations, STEP and IAI, is confusing. Even though there is now co-operation and some compatibility between the two organisations it was difficult to know which to turn to. The difficulty was compounded by the adoption of different sets of jargon.

c) After some effort it was discovered that neither a STEP Application Protocol nor an IAI Foundation Class existed at an appropriate level of detail for our purposes.

d) The data models which do exist appear to have a design bias, and it was concluded that even if detailed models for 'pile' or 'bore-hole' had been completed, they probably would not have met the needs of a contractor. Will they contain attributes such as 'the rig driver's name' or the 'concrete supplier'? Whereas the pile type, e.g. 'driven' or 'CFA', may be regarded as merely a pile attribute to the designer, to the piling contractor they need to be extensive sub-classes.

f) A STEP CASE tool was purchased, but an Object-Store back-end was not forthcoming despite being advertised. It was concluded that the tool would really only have value for larger and more complex data modelling activities.

g) Overall the impression is given that, at the current time, the effort involved in compliance is not justified by the benefits which can be gained for ordinary end-users.

A project pilot was run to test the system integration. The rig acts as the main information gathering point, collecting information throughout the CFA construction process. Pile design information can be downloaded from Object Store at the start of the day/shift, however on multiple rig sites it is not yet known how to distribute the information, therefore for the purpose of the trial, pile design information was down-loaded to the rig by hand. The hardware components involved and the data flows are shown in Figure 7.

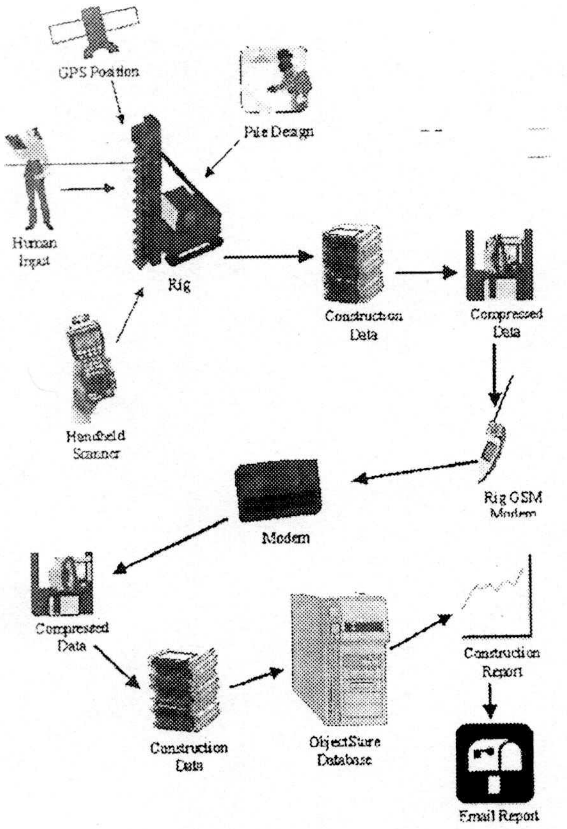

Figure 7
Pilot hardware and data flow

6 INTEGRATION CONCLUSIONS

Integration at both the system and global level remains one of the most challenging aspects of robot development. This is because the activity requires both a clear top-down vision of what is required, together with detailed knowledge of what is achievable from the different available techniques. The following conclusions can be drawn from the two case studies:

1. Even for a relatively self-contained activity such as piling it has become clear that an intensive and highly integrated IT infra-structure is required to optimise business efficiency and maximise the benefits of automation and sensing. It is probable that only object technology can deliver this infra-structure in a manageable form.
2. The problems of establishing industry-wide protocols and data models should not be underestimated. Even when there is genuine willingness to adopt such standards, the problems in doing so currently outweigh the benefits. Perhaps there is a need for the software industry to provide the construction industry with appropriate tools so that the technology is invisible to the user.
3. Introducing new IT into existing organisations presents many short-term problems related to management practices, job descriptions, legal responsibilities and safety. A carefully thought out implementation plan is required

REFERENCES

[1] Fowler, J., *STEP for Data Management, Exchange and Sharing,* Technology Appraisals, 1996

[2] International Alliance for Interoperability, *End user guide to Industry Foundation Classes,* IAI UK Ltd, 18 Devonshire Street, London W1N 1FS. 1996

[3] Inprise 98, see http://netserv.borland.com/

[4] Jardim-Gonçalves, R., Pimentão, J., Vital, M., Sousa, P., Silva, H., Steiger- Garção, 'Roadrobot project - an experience using STEP in construction', *13th International Symposium on Automation and Robotics in Construction,* Tokyo, Japan, June 1996

[5] Laud, A., Bailey, I., '*Understanding STEP - the standard for the exchange of product model data',* publ. Business Round Table Ltd. 18 Devonshire Street, London W1N 1FS, 1995

[6] Object Design 1998, Inc., Burlinton, MA, http://www.odi.com

[7] Seward, D.W., Scott, J., Findlay, J., Kinniburgh, H., "The Automation of Piling Rig Positioning using Satellite GPS", *Automation in Construction*, Vol 6 No.3, pp 229-240, Elsevier Publ. (June 1997)

[8] Seward, D.W., Quayle, S., Mure, N., Scott, J., "Integrating the Business Process with Automation through Object technology in a Foundation Company", *2nd European Conference on Product and Process Modelling,* BRE, Watford U.K. October 1998

[9] Step Tools Inc., Rensselaer Technology Park, Troy, New York 12180, http://www.steptools.com

[10] Wilson, P., Schenck, D., *Information modelling the EXPRESS way,* Oxford University Press, 1993