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Robotic action-heads - New forms of device for attachment to existing construction machines

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Abstract

This paper develops the concept of a range of computer controlled end attachments to construction equipment that' will effectively convert the latter into de-facto large scale robotic manipulators. The paper develops the theory of such devices and then presents data on the development and testing of a full scale prototype system. A range of on site economic applications of this form of technology is examined.

1. INTRODUCTION

Any potential developer of high technology construction machinery, such as field robotic systems, is faced with a major electro-mechanical engineering problem - "How can the requisite large scale pieces of field machinery [1] be developed at an acceptable level of cost?" Highly engineered machines that will do the job - but only on a "NASA" type budget - will clearly not suffice as these will not sell against the existing technically adequate, but low technology, construction engineering solutions.

2. THREE DIFFERENT APPROACHES TO THE DESIGN OF SYSTEMS

Within the context of the economical design of machine systems, three broad design approaches may be taken (i) an a nouveau approach (ii) an adaptation or extension approach or (iii) a functional module approach. Each of these approaches has its pros and cons and each affects differently the cost of production of machinery units - especially one-off units. In the "a nouveau" approach, design is from first principles with custom made components. In the extension or adaptation approach, the designer takes an existing system and modifies it to the current need. In the functional module approach existing "building blocks" are used to create the functionality necessary. This last process tends to be the cheapest and quickest of the three because it avoids specialised and lengthy R&D and special component tooling up costs.

3. DEVELOPMENT OF A ROBOTIC BUILDING BLOCK SYSTEM

The idea of merely "clipping" or "bolting" a number of proven, ready-made and low cost, functional packages together to develop low cost robotic systems is an obviously attractive one. This is especially so if one seeks to be able to operate a "mix-and-match" approach to maximising the utilisation of expensive existing base componentry. The problem though is that, to date, no suitable "clip together" set of construction robot system "building blocks" have existed.

On pondering this problem some 5 years ago, the author became convinced that it should be possible to construct heavy duty robotic arm functional modules and initiated a pro gram was to develop a suitable range of "building bricks" for the heavy duty construction robot creation industry. The first "product" from this pro gram is an "action-head" robotic module.

4. THE CONCEPT OF A "ROBOTIC ACTION-HEAD"

In kinematic form, standard pieces of construction equipment such as mobile cranes back hoe diggers or rough terrain fork lift trucks can be perceived of as simple kinematic chains of parts. Similarly, orthodox robots or manipulator booms are more complex kinematic chains terminated by end effectors [cf for example ret 2]. Figure 1 illustrates the abstract nature of a typical 4 d.o.f planar mechanism construction machine (such as a back hoe and bucket) and a typical revolute joint based 7 d.o.f. robot. At the right hand side of the diagram is the functional difference between the two. This difference is that which has to be supplied to the simpler machine to transform it to the more complex machine. This "additive system" is a defined here as being a "robotic action-head".

Specifically, one may define a "robotic action-head" as a generally compact, computer controlled, stand-alone machinery module that can be attached to the boom of a construction crane, hydraulic excavator or similar piece of fixed or mobile plant to give the underlying piece of equipment effective robotic manipulator and/or tool deployment capabilities.

Ideally the add-on machine should be quickly mountable and demountable, say in less than lO minutes, and should be fully self-contained such that no technical modifications are necessary to the base machine.

5. MODULAR AND VARIABLE FRONT END VERSIONS OF ROBOTIC ACTION-HEAD SYSTEMS

By extending the modularity idea to the design to the action-head system itself, it can be seen that two different form of action-head - a fixed tooling function system and an exchangeable tooling function system can be developed.

In single purpose or dedicated use end-tooling RAH schemes, the action-head is provided with an integral end effect or. This end effect or would normally be a set of jaws. Figure 2 shows a typical integrated form 6 d.o.f. RAH system.

In a second type of scheme the RAH unit itself may be built up from a fixed "base" module and an exchangeable or variable "front-end" module [3]. The general form of this arrangement is shown in figure 3. optional in this set-up is the use of two separate remotely controlled engagement/disengagement modules to allow action-heads and tooling systems to be remotely changed or switched under computer program control.

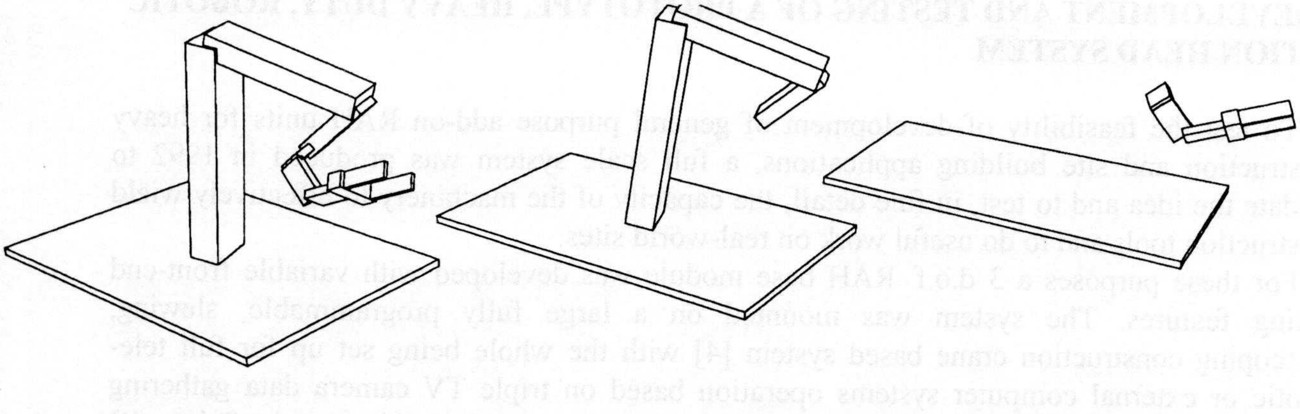


Figure 1 - Definition of a RAH unit as a difference between two functionalities.

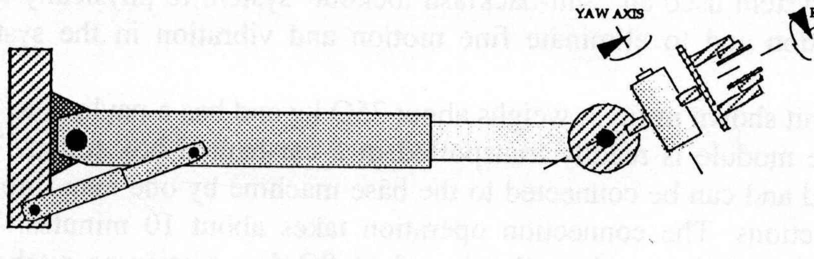


Figure 2 - An integrated form 6DOF action-head unit

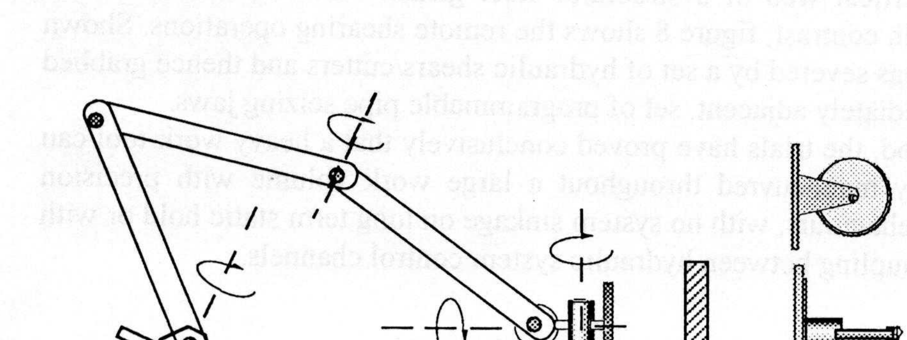


Figure 3 - Schematic of the variable front-end form of RAH unit showing optional remote connect/disconnect modules (RCM's).

6. DEVELOPMENT AND TESTING OF A PROTOTYPE, HEAVY DUTY, ROBOTIC ACTION HEAD SYSTEM

To test the feasibility of development of general purpose add-on RAH units for heavy construction and site building applications, a full scale system was produced in 1992 to validate the idea and to test, in fine detail, the capacity of the machinery to effectively wield construction tools and to do useful work on real-world sites.

For these purposes a 3 d.o.f. RAH base module was developed with variable front-end tooling features. The system was mounted on a large fully programmable, slewing, telescoping construction crane based system [4] with the whole being set up for full tele-robotic or external computer systems operation based on triple TV camera data gathering facilities. The result was a 7 d.o.f., 25O kg payload carrying machine with a reach of about lO metres, with millimetre positioning accuracy and with zero system backlash.

The elements of the system are illustrated schematically in figure 4. Figure 5 shows the 3 d.o.f. "wrist" system employed as the RAH base module. Three different tooling systems in the form of a saw, a drill and a gripper/cutter-shear system were developed and deployed.

All functions of the base machine and the action head and tooling system were set up under a remotely controllable, continuously variable action, electro/hydraulic valve systems. In addition the action head system used an "anti-backlash lockout" system to physically lock all joints during tool operation and to eliminate fine motion and vibration in the system during physical operations.

The 3 d.o.f. base RAH unit shown in fig 5, weighs about 25O kg and has a payload to self weight ratio of under l. The module is readily transported in a car-hauled box trailer. The system is fully self contained and can be connected to the base machine by one man through snap and screw type connections. The connection operation takes about 10 minutes. The system provides +/- 18O degree motion on the roll axis and +/- 9O deg. motion on pitch and yaw axes.

Three specific tooling systems - namely a 35O mm diameter hydraulic circular saw, a SO mm diameter drill and a combination gripper/shears system - were developed and successfully deployed under full remote control operation. Figure 6 shows the saw system. Figure 7 shows the results of remote drilling operations in the form of a 5O mm hole that has been drilled through the vertical web of a structural steel girder. Note the cleanness and accuracy of the hole edges. In contrast, figure 8 shows the remote shearing operations. Shown is a 4O mm steel pipe that was severed by a set of hydraulic shears/cutters and thence grabbed and held by a parallel, immediately adjacent, set of programmable pipe seizing jaws.

Over a 6 month period, the trials have proved conclusively that a heavy work-tool can be smoothly and dextrously manoeuvred throughout a large work volume with precision control, with no run-away behaviours, with no system sinkage on long term static hold or with no cross-torque or energy coupling between hydraulic system control channels.

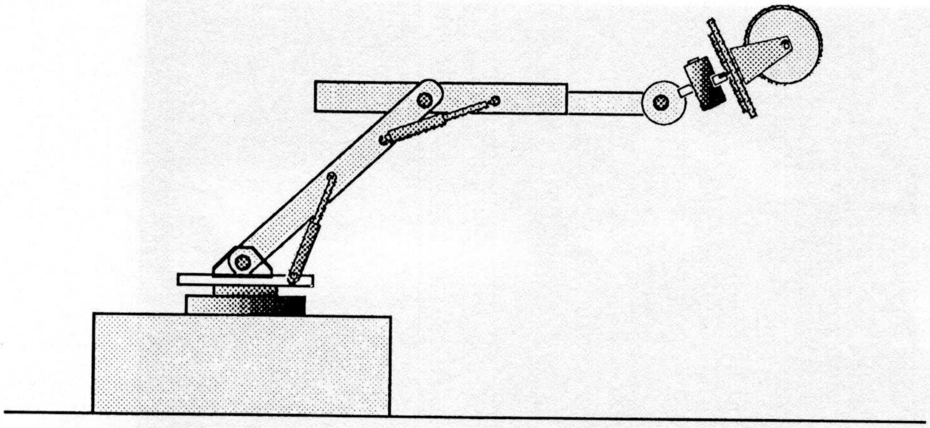


Figure 4 - The overall system - made up from three independent functional systems

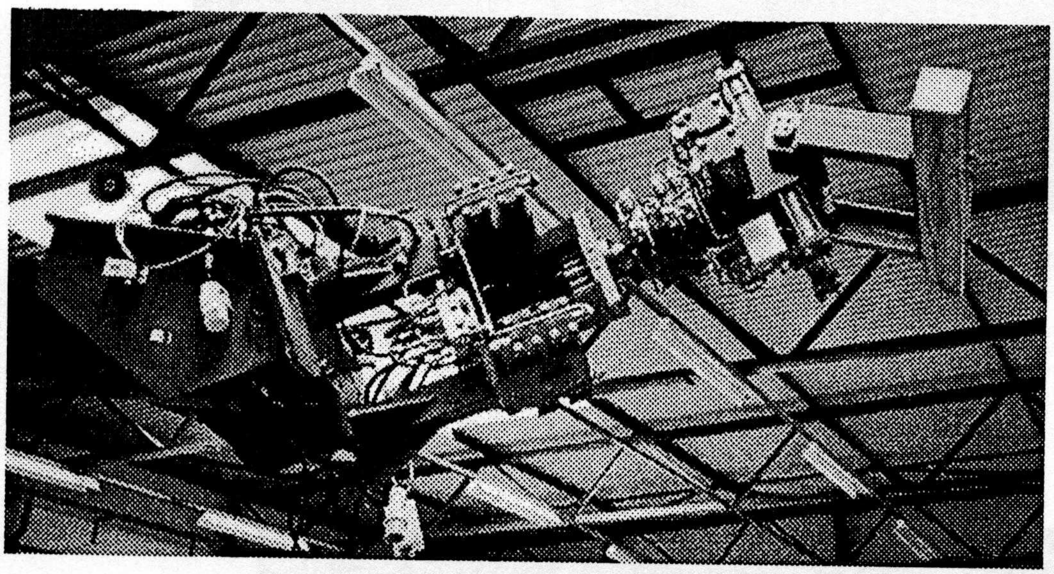


Figure 5 - The 3DOF RAH base module in operation with a 250 kg test load as a front-end

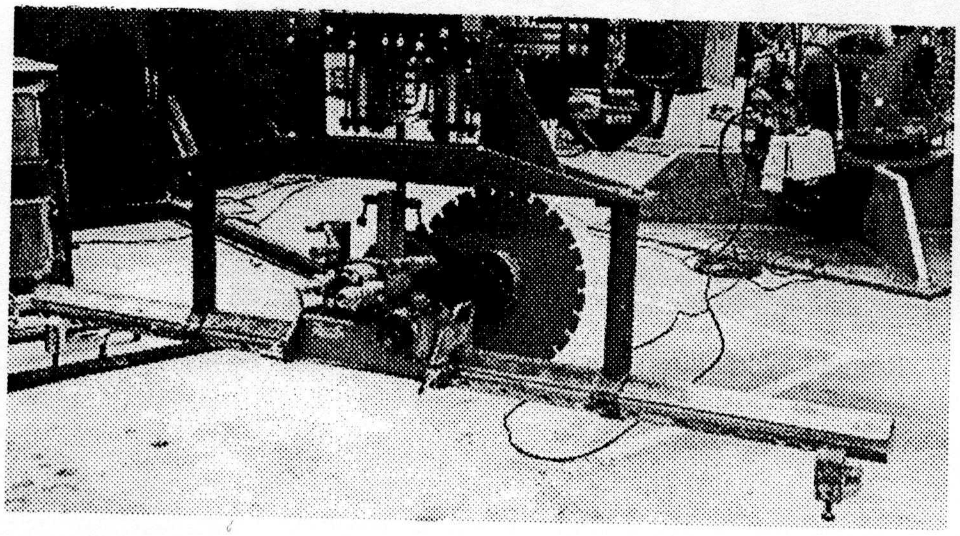
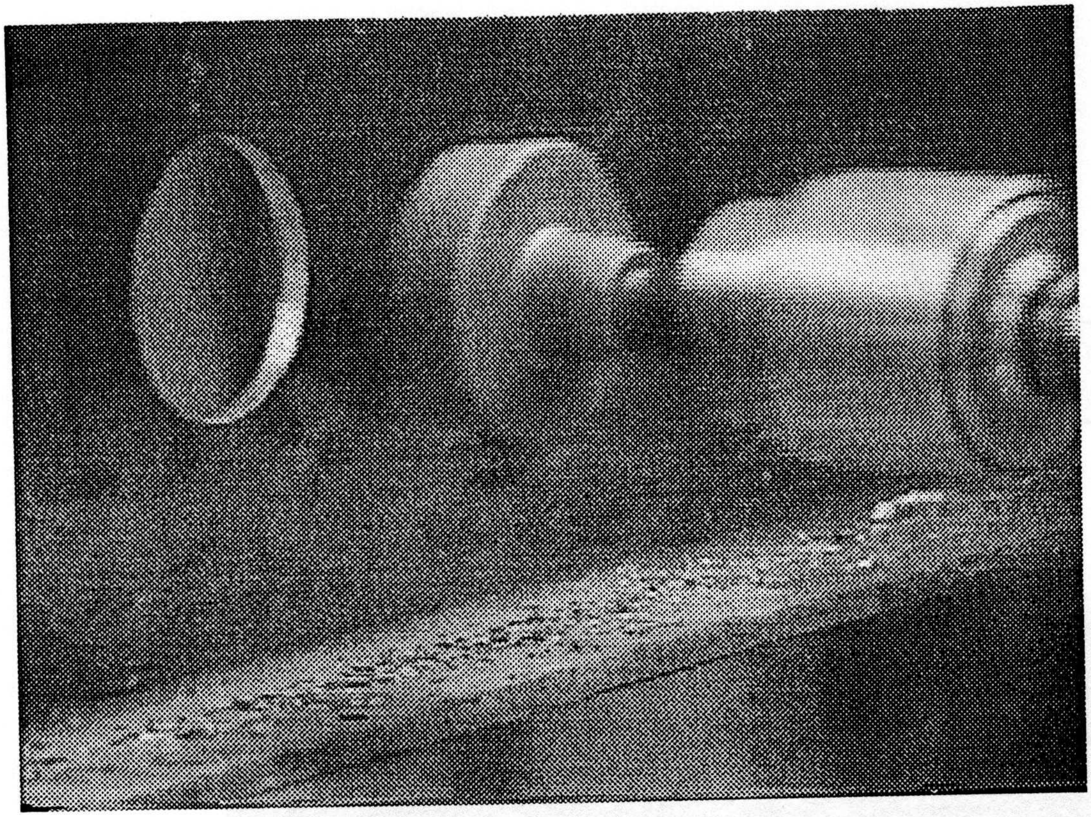


Figure 6 - RAH base module with hydraulic



Figures 7 Remotely drilled hole in the web of a steel girder {photo grabbed from videotape}

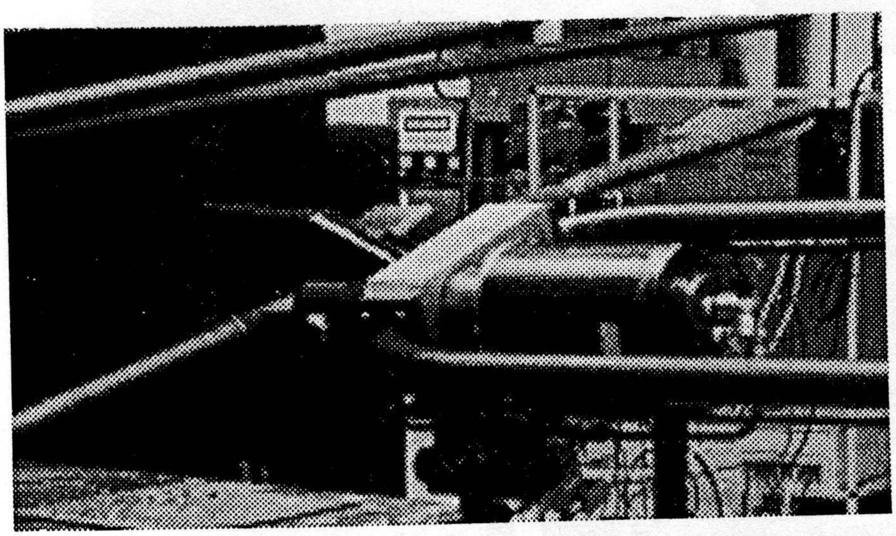


Figure 8 Remote hydraulic shearing and holding of 40 mm steel pipe

7. SOME ILLUSTRATIVE SCENARIOS FOR POSSIBLE RAH SYSTEMS USE

7.1 Use in a context of materials storage yard activities.

In materials storage yards, truck unloading areas and in fabricated assembly lay-down areas [cf ref 5] a "prosthetic hand" type RAH unit might be attached to a rough terrain telescoping boom mobile crane operating as a yard server. By having a set of remotely controllable, exchangeable, precision gripper systems, with possible force feedback controls to it, there will be no need for a dog man or crane chaser to sling loads, such as pipes, valves or structural steel work, since all activities may be carried out from the driver's cabin. Furthermore there is no need for a person to walk upon loose materials stacks and suffer possible injury through materials movement. Thus only one person is needed rather than two and safe operation is possible in wet or cold weather and in environmentally hazardous areas.

7.2 Use in a context of concrete pipe laying operations

In deep trench concrete pipe laying activities, the work is commonly executed with a hydraulic excavator and a team of 2-3 men. Excavation and gross pipe positioning operations are done by the excavator and pipe detachment, fine trim and fine pipe positioning are done by men working within the trench. By use of a RAH unit, which may be carried on the excavator in a tool "holster", all operations should be able to be carried out from the surface by the action of one man. This gives not only immediate direct labour savings but also in some cases there may be very large savings from not having to shore the trench. Most safety regulations require that trenches be supported if men are to enter them. With remote action pipe laying no shoring is necessary since no workers enter the trench.

7.3 Use in a context of access and support scaffold erection

Detailed three dimensional interactive computer simulation studies have been carried by the author [cf 6] concerning the problem of robotic erection of scaffolding systems. These studies have confirmed that it is very possible to use a standard rough terrain crane (say), with a precision RAH gripper on its end, to erect large dimension tube and coupler scaffolds or unit frame type scaffold and form work frames. In the total erection process basically no human intervention is necessary. The conclusions from these studies are that scaffolding can be erected safely under all weather conditions and that the very large amount of man-handling entailed in the process can effectively be totally eliminated. Also through the mechanised process, larger and heavier frame systems are possible, process times can be very substantially reduced and general safety greatly improved.

7.4 Use in a context of concrete foundation installation

By the use of a number of exchangeable RAH units, a single hydraulic excavator (for example) can be transformed into a total "construction work-station". Thus in the construction of, say, a 3m x 3m x 2m bridge or building foundation the excavator can firstly dig the hole and thence by attachment of appropriate variable front-end RAH units place the reinforcement bars in position, tie the bars together and thence in conjunction with a concrete pump delivery system place the concrete and appropriately deploy an immersion vibrator to compact it. Thence the machine could deploy a variety of screeding and finishing tools to surface finish the concrete and apply curing compound. If desired the whole can be under computer control operated from a CAD package description of the finished product.

By extension of this total work-station concept, simple robotic systems can be set up to build house slabs, create slip-formed building services cores or to create flexible concrete products creation work cells within concrete products factories. A long list of discrete region, robotic work-cell type applications could be developed.

7.5 Use in a context of light framed steel building erection.

Within the environment of steel framed house or factory construction, a standard hydraulic boom crane equipped with a prosthetic hand type RAH unit could be used as a materials positioning system. One step placement of elements from truck to unit final position is possible. Accuracy of placement of, say, a 5 metre long cold formed steel purl in, can be to within a few millimetres at reaches of 2O metres and the element can be placed in correct plumb and alignment against all three 6 axes of motion. By action of a second arm or second pass with a fixing tool, permanent fasteners could be installed. In the whole process, no rigging personnel would be necessary and the operation hence safe and weather insensitive. In addition the individual pieces of steel could be bar coded for random order truck delivery.

7.6 Use in a context of concrete production yard operations

In small production process operations - as for example in gantry serviced site precasting or factory operation - low cost process automation systems can be installed by suspending a heavy duty variable front-ended RAH unit from a travelling gantry. The RAH unit can then deploy a number of tooling systems and devices as well as acting as a general products manipulator and positioner. The RAH system would be a standard off-the-shelf module that could be moved as desired or re-used elsewhere once the job was finished.

8. SYSTEMIC BENEFITS OF THE ACTION HEAD APPROACH

Robotic action-heads are believed to have a strategic or systemic economic advantage over integrated-form robot arms in the site engineering context. Large robotic arms, such as the Esprit pro gram's LAMA system, are expensive to purchase and are large dedicated machines that would have a low general utilisation factor on normal construction work. Also the machinery is physically large and indivisible. It has to be mounted on its own road vehicle or to be transported to the particular site, with consequential high equipment floatage charges.

Action-heads, in contrast, can pay for themselves by adding utilisation potential to machines that contractors already own and which are otherwise "earning their living" doing other things. The RAH units do this by extending the range of useful work "do-able" by a particular form of machine. Thus if one has a hydraulic excavator which might be currently idle in time of rain or in times of lack of excavation work, one can add an action-head to it and it can become a bridge inspection device or underwater repair device [7], a sand blasting or shotcreting machine, a falsework erection machine or a concrete house foundation and frame installation machine.

A further feature of action-heads is that they are sufficiently cheap to have one unit on every site or to be held as hire items by local contractor's plant leasing firms. This allows low transport charges to individual sites and the costs of the RAH apparatus can be amortised across many diverse jobs and projects.

Benefits may be expected from the introduction of low cost robotic arm technology and associated smart software.(i) At the site or work task level through lessened site labour and better safety (ii) at the overall firm level through greater resources flexibility and responsiveness (iii) at the project and industry level through improved project delivery times, quality and cost.

CONCLUSIONS

At its outset, this paper proposed the idea of robotic system modules as a possible strategy for the low cost synthesis of robotic construction machines and for the improved utilisation of existing stocks of nominally non-robotic construction equipment. Subsequent to the successful field trials of some specific modules, as has been described here, it is now concluded that modular robotic systems for the construction industry are technically feasible and commercially viable. Further, based on preliminary cost-benefit studies of selected applications areas, it is suggested that this technology has very considerable immediate, as well as future, building and construction industry potential.

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