A unified theory of construction robotics

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Abstract

Presented is a unified theory of construction robotics based upon the idea of behaviour programmable physical action units and modules. The theory covers both animate and inanimate construction machines and the paper gives examples of the theory’s use to model dynamic systems composed of, disparate-form, active agents. Some new ideas for intelligent controller systems for smart machinery systems are presented.

1. Introduction

Despite some very great strides having been made in recent years in the area of field and constructional robotics, the discipline and the efforts within it are extremely fragmented and disconnected. In the main, this is due to the non-existence of any fundamental theory to cover the whole field of construction robotics and systems. The aim of this paper is to develop a unified view of the discipline, to map the field’s abstract structure and to merge the new ideas of construction robotics with more traditional forms of construction machinery. It attempts to do this by developing a general theory of construction systems based upon the proposition that construction occurs as the result of cumulative action of sets of behaviour programmable physical agents and powered machines.

2. Terminology

Within this paper the term „machine“ will be taken to mean „a powered mechanism capable of doing mechanical work“. The notion of „a programmable machine“ is taken to mean a machine that can be reconfigured to perform different activities by means of a to set of instructions. The instructions may be given through changes in hardware or in software [1]. The idea of a programmability in machines is a centuries old one and probably originated with the invention of the Jacquard loom in 1801 [2]. In this paper the notion of programmability is further extended to include a machine whose behaviour is not preprogrammed but can be altered ‘on-the-go’ by a series of external instructions. Thus, a motor grader can be considered to be a multi-degree of freedom, blade-wielding, tractor whose internal geometry and power parameter can be changed, by N-control levers- as the machine is doing work (i.e. in real time).

The term ‘capital’ is used here in its technical economic sense to mean any piece(s) of physical apparatus that might be employed in a physical production process. The word is used here to mean ‘all the tools and equipment incidental to the production of other goods’ rather than in its everyday accountancy sense of cash or money. Construction then is a process requiring people, energy and capital. Capital can be further divided into passive tools and equipment and powered machines.

3. Physical Capital and Construction Processes

Civil engineering and building activity involves technical processes that are generally capital intensive. That is, they require large amounts of specialised physical equipment and tools. Thus, tunnelling operations may involve the use of millions of dollars of rock drilling equipment, shotcreting machines, dewatering pumps, electric locomotives and self-erecting tunnel forms. Similarly, earthmoving activity and foundation construction may involve the application of fleets of bulldozers and open body dump trucks coupled with diesel-powered pile driving hammers, ground ripping equipment, ground anchor installation equipment, prestressing jack systems and the use of heavy cranes and off-road articulated dump trucks. Likewise, high rise building may involve much manual labour, explosive power-tool use, the use of self climbing tower cranes and ultra-high pressure concrete pumps. Motorised machinery, which is controlled by people or computers, plus passive objects comprises an overall project’s physical capital.

4. Development of a Universal Model of Construction Machines

We propose here a universal-form modular model to cover all types of motorised construction machinery systems - both robotic and non-robotic. Figure 1 indicates the abstract structure of construction machines. The model includes the functional elements that constitute a very wide range of construction machines, system types and power tools. Both human workers and inanimate machinery types are covered by the model. The abstract machine is information driven and real-time, behaviour programmable. In the model, the control system can be a human (acting in an operator-in-the-loop mode) or a computer system. The model presumes a system of external sensors but it can be modified, if necessary, to include internal sensor systems. The most common type of operator interface is the rate control, such as in valves and throttles. Position controls such as steering wheels and the like, however, may also be used. In some systems only one or two of the modules may be evident. i.e. the last module may be null. Thus, a hand power drill my only have the motor and active structure module.

The generic machine of figure 1 can be adapted to carry passive loads or various types of active payloads such as instrumentation packages or supplementary tool systems. The model covers traditional, one-arm, fixed base robot systems as well as multi-limb systems. In this context the term "mobility platform" includes conventional wheeled and tracked undercarriage systems. It also embraces the various forms of legged construction locomotion systems that are available. The mobility platform idea also covers locomotives, in-mud screw propulsion systems, barges, and flying machines such as helicopters. In the model, the term 'active structure' refers to any serial or parallel-topology variable geometry structure or powered mechanism. This term covers gantries, scissor-lifts, and knuckle booms as well as backhoes and all forms of loader mechanism. It also applies to many other machine types - irrespective of their particular kinematic form. It also covers crane-based gravity pile driving hammers with leaders, auger screw systems and impact hammers. In figure 1, the term active structure is used in the plural. This is to allow for the fact that some construction machines, such as wheel loaders with backhoes, can carry two or more kinds of active device. The schema allows for modular machines, piggy back systems, robots and manipulator arms with grippers and powered end effectors and reconfigurable machines [3]. The unit of figure 1 will typically contain a power source in the form of an energy transducer or heat engine plus some form of complex kinematic chain.

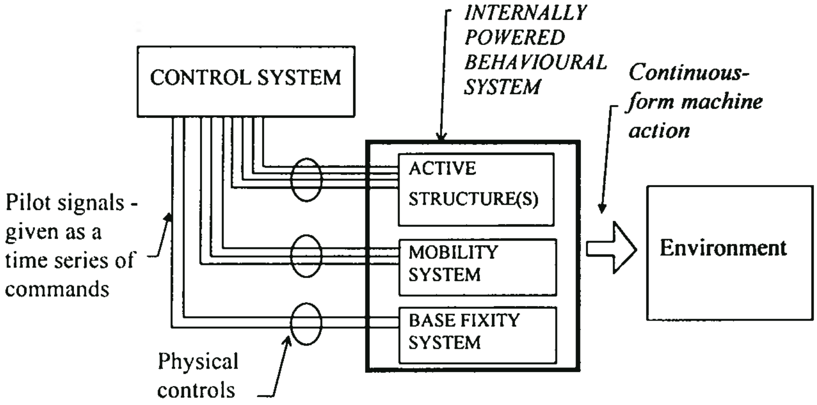

Figure 1. A proposed universal model of construction machines

6. Illustrations of the Use of the Model

The model of figure 1 is intended to cover a range of machines. These may range from self-propelled scissors lift and towed roller systems through to complex multiple degree of freedom system such as motor graders and legged tool carriers such as the Kaiser Spyder. It also covers rock drilling jumbos, tunnel boring machines, asphalt paving machines, concrete transit mixers and truck-based mobile cranes. Also included are drilling barges on jack-up spuds, rear-dump trucks and tungsten carbide-tipped rock saws. Construction tractors, with and without such attachments as bulldozer blades and rippers or scraper bowls or trailer systems are also embraced. Mobile builder's hoists and self erecting cranes are also covered. Archimedian screw mixer systems carried on rail cars - as used in tunnel lining - are also covered. The model also covers special type of machines such as self-propelled concrete power trowelling machines and tele-operated terrain survey vehicles. Active falsework systems are also included.

An example of a construction machine of complex type that can be modelled is the laser controlled, telescopic-boom, concrete screed system of figure 2. Clearly visible is the active structure plus the mobility platform and jack-up base fixity platform.

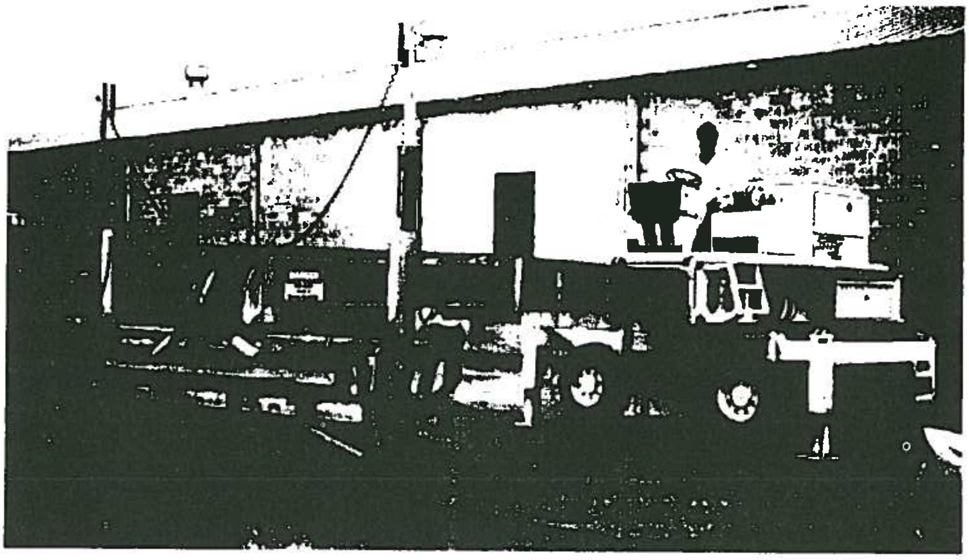

Figure 2. Multi-degree of freedom, mobile tool-handler/concrete-screed-system

7. Suggested Uses of this Model

Since this model is a black box representation of a system, it is of course silent about the internal nature of the machine itself. The model's primary use is to investigate the action control aspects of field systems and to look at process initiation and management issues as well as at active agent deployment strategies. A suggested main application is in understanding the mode of use of the machine either alone or, perhaps more interestingly, in active cooperation with other different type of machine unit and human actors. Thus, the model may be used to study trucks depositing material into the rear of asphalt pavers, transit mixers delivering concrete into concrete pumps and twin cranes lifting a common load. A further application of the model is to look at the strategies-of-use of machines as they relate to the accomplishment of purposive tasks. Alternately, one can look at processes that involve gaming with nature. A special use of the model can be to describe the use of humans or scout survey vehicles when they are used as spotters and mobile information gatherers in conjunction with, say, heavy earthmoving operations.

8. An Illustrative Use of the Model to Investigate Problems of Multi-Machine Management

A potentially very interesting use of this model is in analysing the control processes required to maintain a fleet of different machinery types operating close to each other. In these circumstances the machines may all be operating within the same physical area. Of necessity, under these conditions, the machines may have to negotiate priorities and space usages. Also, each machine may be operating autonomously. A common construction situation where spatio-temporal machine coordination is required, and where machine mutual interference occurs, is when delivery-trucks, dozers and compactors work together on the top of an earthwork embankment (figure 3). Another case is when multiple machines have to operate in the tight confines of tunnels.

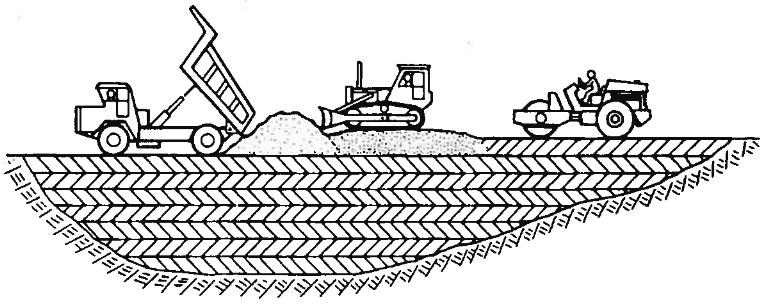

Figure 3. A sample multi-agent operation

Figure 4 represents a model of a three active-unit mutual interaction system of the type of figure 3.

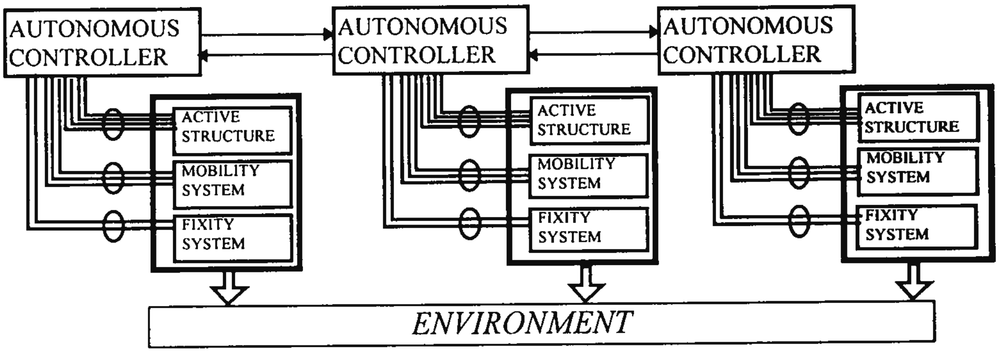

Figure 4. A model of a three-machine cooperative work-system

For coordination to occur within this organisational structure there must exist bi-directional communications links between any inanimate actors in the system. The diagram, however, still applies even if the machines are people and one is referring to a human work-team rather than to a machinery fleet. The diagram also covers special cases - such as when one active earthmoving machine push-loads another.

9. An Example Analysis of Heavy Machine Process Control

To illustrate the use of the programmable machine model in a construction context, suppose that we are looking at a bulldozer acting to remove a portion of earth to cut a trench. In this case, the base mobility machine is a high powered crawler tractor. The positively-powered active structure is the blade plus its double acting up/down hydraulic ram. Figure 5 shows the necessary control-lever commands for the development of a flat bottomed cut. These commands are the actual ones required and were developed from detailed studies of actual bulldozer cutting experiments. The studies were performed at the Australian Army's construction machinery proving grounds in Sydney, Australia.

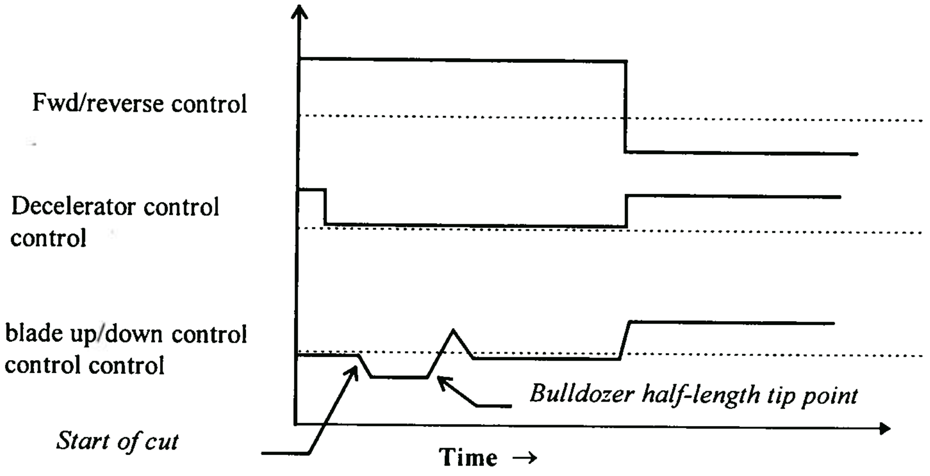

Figure 5. Analysis of an elemental behaviour episode in the operation of a bulldozer

Clearly, a number of small behaviour episodes will chain together to yield a full field task. In practice, the use of the blade up-control as the bulldozer tips-forward is critical. If the blade is left in a fixed position the bulldozer progressively cuts into the ground. As it does so, the machine enters into an exponential digging phase. The piece of equipment then totally digs-in and stalls. This happens irrespectively of the power of the bulldozer or of the nature of the soil. The diagram of figure 5 is also intended to demonstrate that it is the instruction set that determines the physical effect created by the machine. This means that the 'task' aspect of construction activity is contained in the software not in the hardware or in the environment. The same machine can be deployed variously to produce many different effects and task outcomes. The same system can produce many artifacts.

10. Programmable Functional Operator Theory

In parallel with the foregoing development of the unified machine model, and complementary to, it is possible to develop a number of new ideas relating to programmable functional systems and to programmable functional operators. For civil engineering and building process analysis purposes, three types of functional operator can be developed. These are named as 'the action operator', 'the materials delivery operator' and the 'materials removal operator'. Alternatively, the action operator can be modelled as a programmable force vector. More discussion of the theory of functional operators is given in [3].

10.1. Spatial Operators

Spatial operator notions can be used to describe, in a convenient and powerful manner, construction processes and to set them up for simulation modelling. For example, consider the operation of a heavy vibrating roller (figure 6) in the compaction of earthworks. For technical reasons, the action of the compaction machine in real life requires certain rolling patterns (figure 7) be adopted [4].

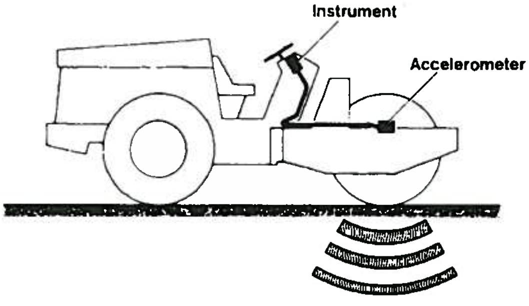

Figure 6. Schematic of a mobile vibratory roller compactor

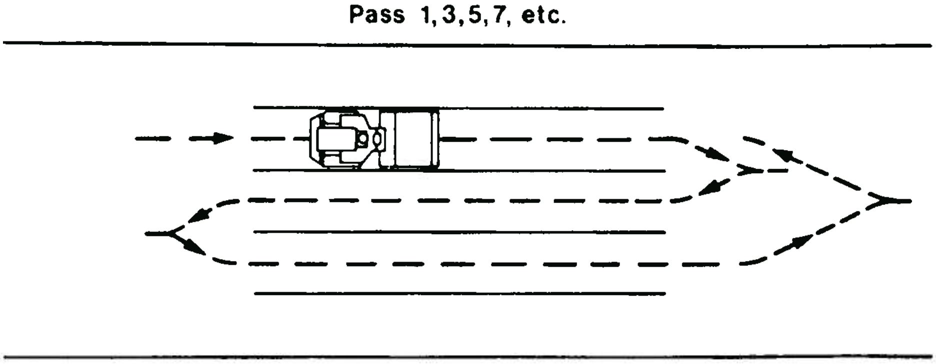

Figure 7. Rolling pattern for earthworks compaction

This activity is normally undertaken in association with a programmable materials delivery operator. For clarity of exposition here, though, this latter operator will not be included in the discussion. If we view the compactor machine as a both space and intensity programmable mechanical action machine, we can then represent this resource by a „token" applied to a „place". If we do this we can then develop operations-maps such as that illustrated in figure 8. We can also develop discrete-event, state-model simulations of the spatio/temporal behaviour of such systems. One method that shows much promise in this regard is the method of Petri-Nets [5]. Alternatively, we can look at how a machine must be programmed in space-time to generate a particular behaviour or to interact with another spatio-temporally programmed machine or smart-agent.

In figure 8, behaviour through time can be further modelled by assigning dwell times to tokens in cells or by developing the cells as voxels. That is, by developing a time axis at right angles to the plane of figure 8. Thus, one can have a 'cube' of 'places' as a type of finite state machine through which tokens can 'migrate' as a function of time. The intensity of action of the operator at each place however has to be modelled as some variable property of the operator.

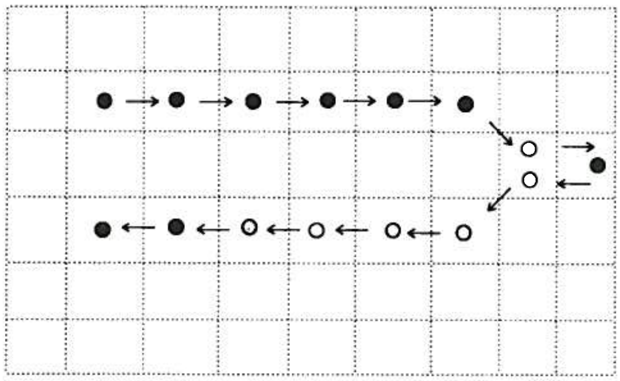

Figure 8. A token-place model of the behaviour of a variable-action mechanical operator

From these ideas and those of on-the-run programmability, it is clear that one can program machines to execute „behaviours“- as high order planning units - rather than viewing machines only in terms of low-order activities like programming in 'joint-space'.

11. Robots as Programmable Machines

From the above discussions, if we define a 'robot' as a behaviour programmable construction machine and if we see most traditional construction machines as operator-in-the-loop programmable systems then it would now seem clear that there is no essential difference between construction robots and existing construction machinery systems. The only real difference is in the mode of programming. The author has also argued previously the essential similarity between cranes, manipulators and standard manufacturing robots [6,7]. This idea has now been extended to asphalt paving machines, tunnel boring machines and rock drilling systems. Under the skin, they are *all* the same.

12. Cognitive-controller-systems Development

If the only difference between standard construction machines and construction robots is their mode of programming, then the matter of the design of a generic form cognitive box (of sufficient intelligence to drive multi-degree of freedom machines in complex environments) is the only serious technical design hurdle standing in the way of the manufacture of sophisticated construction robot systems. Some of the technical aspects of the designing high IQ cognitive drivers for task based construction machinery system has been addressed to a degree in [3,8].

13. The Prospects for Genuinely Smart Self-Programming Construction Machines

One aspect of the proposed general/unified model outlined here that it focuses attention on the real difficulties of environmentally-interactive machinery control in unknown environments. The evidence of figure 5, suggest that the control process must be real-time, interactive and sensor based. Typically, force and position cognitive control processes are required. What is needed by the construction machinery industry is some sort of further higher order control system that will plan the 'task' and then work out what series of control actions will get the machine there - given that the parameters of the environment may only be approximately known. One possible solution here might be the use of context-general, reasoning-system-based cognitive box operating under sensor based reactive control [10].

14. Development of a Universal Controller Box

One important implication of this programmable construction machine theory is that, under-the-skin, all construction machines are the same - in that they may be controlled by information signals. This suggests that it is possible to build one only, *universal* construction machine controller box that can fit all machines and all situations. This single box idea has great potential economic value - in that it means that earthmoving machine developers, autonomous truck developers, crane machinery developers and concrete trowelling machine developers can share the same, high level, intelligent construction machine controller box. This observation suggests that major economies of scale can be developed and that for the same amount of money very much more sophisticated general purpose controllers can be developed than is possible for one-off project developments.

15. Use of Robotic Concepts to Model the Action of Construction Workers

In conjunction with figure 1, it was suggested that human action and robotic machinery were essentially of the same nature. From this observation, it becomes evident that using robotic systems design concepts - such as inverse kinematics and Jacobians - it should be possible to model and simulate human action in a manner and degree of accuracy hitherto impossible. Indeed the US robotic systems simulation company, Deneb has developed a system for factory workplace analysis, ergonomics and general assembly simulation using these principles. Their system is called Ergo [9]. Such a system is now being further extended by the writer's group. The intent is to develop a research tool for scientific investigation of the physical and cognitive ergonomics aspects of construction work and for specific Occupational Health and Safety analyses.

16. Conclusion

In this paper, a unified abstract-theoretic view of human and in-animately programmed construction machines and machinery systems has been presented. By developing a high level of abstraction model of a construction operator (fig 1) the identicality of the fields of traditional construction machinery, human action and construction robotics has been shown. Whilst there are very obvious hardware differences between systems the abstract form of the system in use is identical. By perceiving that traditional construction machinery and robotics occupy a continuum, it is hoped that more generic form research might be possible and less fragmentation of research effort developed. Further, through the use of various time-series of commands complex systems comprised of man machines can be dynamically modelled and virtually prototyped. From this we can see that whilst the end-result of construction flows from the actions of the machines perhaps the essence of the construction process lies in the instruction sets that are given to the machinery systems. This suggests the somewhat radical conclusion that construction is a principally a software problem rather than a hardware problem and that programmable machines and robots are absolutely central to the overall process rather than some kind of new genre machine type.

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