A Universal Framework for Field Robotics

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Abstract

This paper present a general paradigm for the development of mixed man and robot systems for the execution of industrial fieldwork operations. The theory covers both animate and inanimate fieldwork systems and is based upon the idea of behaviour programmable physical action units and modules. The paper gives examples of the theory's use to model dynamic systems composed of individual systems and fleets of, disparate-form, active agents. Some emerging applications of mixed fleet robot systems in construction, agriculture, forestry and mining are presented.

1 Introduction

The modern fields of agriculture, mining, forestry, shipbuilding , civil engineering, and assets maintenance, for example, are capital and machine intensive large scale industrial activities. Automation of these activities is difficult because any new systems must operate within the context of existing methods and processes and must be compatible with current mixed manual and mechanized operations. To date, the development of robot systems suited to these, non-greenfield, operations has been hampered by a lack of a general theory of field robotics in the context of practical work-doing industrial situations. Such a theory is required to guide designers in the synthesis of suitable machinery systems to suit the real marketplace and as well to unify efforts across what seems to be initially quite disparate sector disciplines.

The aim of this paper is to present a, high level of abstraction, theory of work-doing mobile robotic systems and for the fleet use of such systems. The aim is also to show how some new ideas of field robotics can merge seamlessly with more traditional forms of industrial machinery. The paper attempts to do this by developing a general theory of fieldwork systems based upon the proposition that deliberative environmental change occurs as the result of the 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 [Mair 1988]. The idea of a programmability in machines is a centuries old one and probably originated with the invention of the Jacquard loom in 1801 [Gunn 1982]. In this paper, however, the notion of programmability is further extended to include a machine whose behaviour is not just pre-programmed but which can be altered 'on-the-go' by a series of external instructions. Thus, a construction 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. Fieldwork 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 fieldwork Processes

Agricultural, mining, construction and forestry type activities nowadays involve technical processes that are generally capital intensive. That is, they require large amounts of specialized physical equipment and tools in the form of tractors, cranes, pumps, drill-systems, power saws, electro-hydraulic jacks and so on. Thus, a typical civil or mining tunneling operation may involve the use of millions of dollars of rock drilling equipment, shotcreting machines, dewatering pumps, electric locomotives and self-erecting shoring systems. Similarly, land clearing and open cut mining may require extensive earthmoving activity and the use of heavy loaders and haulage vehicles. Crop production may use tractors, balers, harvesters and so on. Likewise, many industrial operations require the use of heavy lifting equipment and mobile cranes. Motorised machinery, which is controlled by people or computers, plus passive objects comprises the requisite physical capital an overall project or process.

4 Development of a Universal Model of Fieldwork Machines

In a previous paper [O'Brien 1997] a universal-form modular model to cover all types of motorised fieldwork machinery systems - both robotic and non-robotic - was presented. Figure 1 indicates the abstract structure of an archetypal fieldwork machine. The model includes the functional elements that constitute a very wide range of fieldwork 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 may only have the motor and active structure module.

In the model, the term 'active structure' refers to any serial or parallel-topology variable geometry structure or powered mechanism. This term covers gantries, scissors-lifts, and knuckle booms as well as backhoes, powered augers and all forms of loader mechanism. It also applies to many other machine types -- irrespective of their particular kinematic form.. In figure 1, the term active structure is used in the plural. This is to allow for the fact that some fieldwork machines, such as wheel loaders with backhoes, can carry two or more kinds of active device. 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.

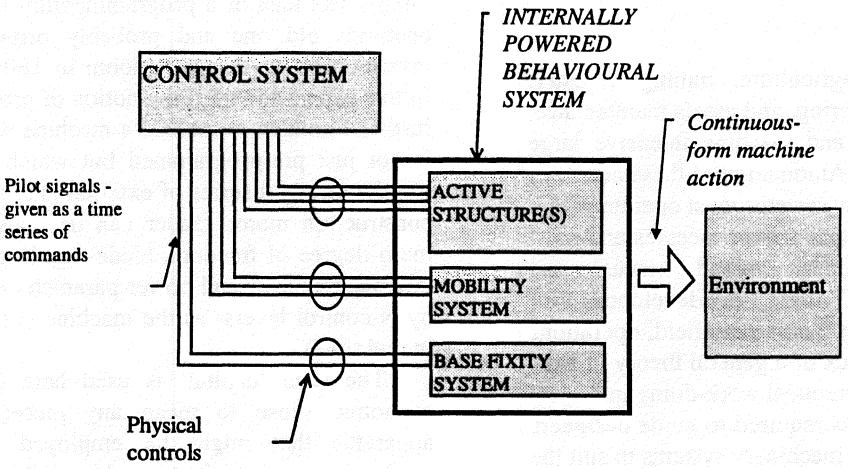

Figure 1 -- A proposed abstract-form model of a fieldwork machine

5 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.

An example of a fieldwork 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.

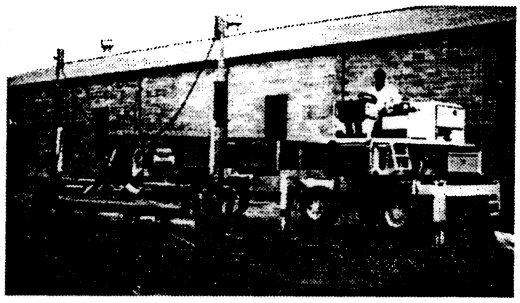

Figure 2. An example, multi-degree of freedom, mobile tool-handler/concrete-screed-system

6 Suggested Uses of this Model

The main use of figure 1 is to model the action of single robotic machines and groups of such machines [O'Brien 1997]. Thus, the schema may be used to model the interaction of fleets of disparate-type, operator controlled or robotically controlled, machines on mining sites, in agricultural operations or in forestry or construction sites.

7 An Illustrative Use of the Model to Investigate problems of Multi-Machine Management

A potentially very productive use of this model is the analysis of 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 a common physical area. Of necessity, under these, close-coupled, conditions, the machines may have to negotiate priorities and space usages. Also, each machine may be operating autonomously. A common fieldwork situation where spatio-temporal machine coordination is required, and where machine mutual interference occurs, is when material delivery-trucks, spreader-equipment and compactors work together on the top of an earthwork embankment (figure 3). Another case would be where multiple machines have to operate within the tight confines of a tunnel or shaft.

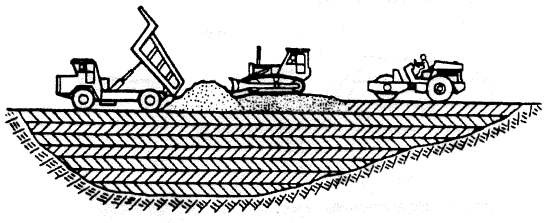

Figure 3- A sample multi-agent operation

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

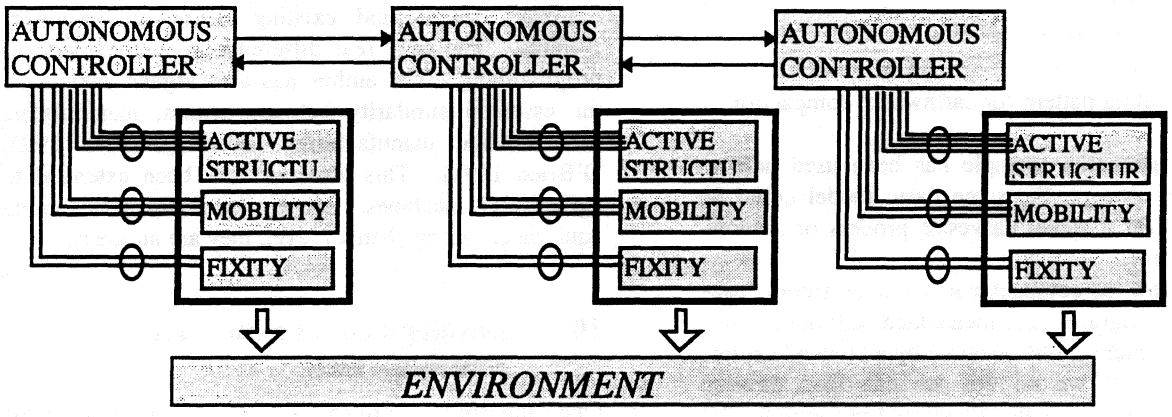

Figure 4 -- A model of a three-machine cooperative work-system

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.

8 MODELLING MOBILE MECHANICAL-ACTION OPERATIONS

Spatial operator notions can be used to describe, in a convenient and powerful manner, fieldwork 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 [Forssbladd 1981].

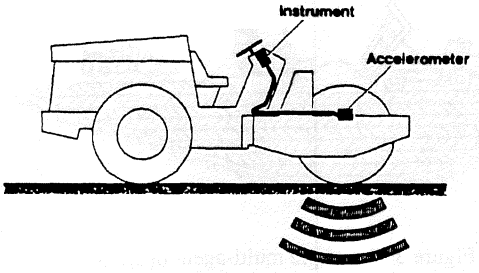

Figure 6 -- Schematic of a mobile vibratory roller compactor

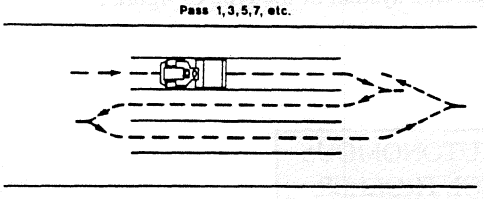

Figure 7 -- Rolling pattern for earthworks compaction

Whilst an earthworks example has been used here to illustrate the concept, the same basic model could be used equally for a wheat harvester process or a snow-clearing process.

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 [Wakefield et al 1997]. 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.

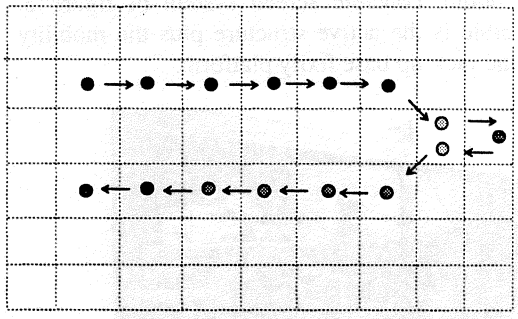

Figure 8 -- A token-place model of the behaviour of a variable-action mechanical operator

From these ideas and from 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'.

9 Robots as programmable machines

From the above discussions, if we define a 'robot' as a behaviour programmable fieldwork machine and if we see most traditional fieldwork machines as operator-in-the-loop programmable systems then it would now seem clear that there is no essential difference between fieldwork robots and existing fieldwork 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 [O'Brien 1995, O'Brien 1991]. This idea has now been extended to agricultural machines, forestry machines and mining equipment. At an abstract level, they are all the same

10 Development of a universal controller box.

One important implication of this programmable fieldwork machine theory is that, under-the-skin, all fieldwork machines are the same -- in that they may be controlled by information signals. This suggests that it is possible to build *one* only, universal fieldwork 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 agricultural machinery developers can share the same, high level, intelligent fieldwork 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. This notion has been previously discussed in some detail in [O'Brien 1997]

11 Modeling mixed man-machine operations and activities.

In relation to figure 1, it was suggested that human action and robotic machinery are essentially of the same nature. From this observation, it becomes evident that using robotic systems programming concepts (such as direct joint programming or through the use of teach points and inverse kinematics) it is possible to model and simulate human action in a manner and to a degree of accuracy hitherto impossible.

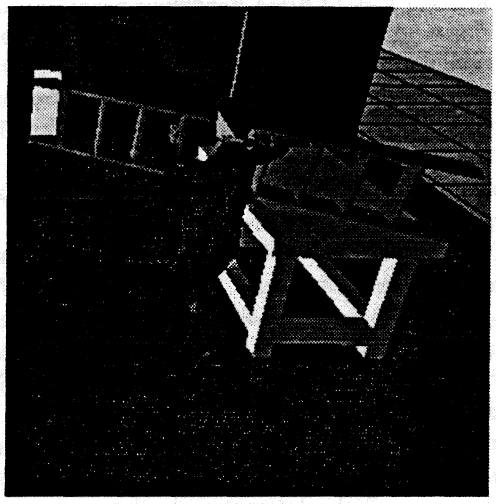

Figure 9a - Human activities dynamically modelled using programmable machine concepts

Figure 9a, for example, shows a worker, modeled as a humanoid robot, in the process of setting up a ladder to wash a window. Figure 9b shows the worker wiping the window with a rubber blade. Figure 6.2 shows the type of programmable skeleton idea that was used.

The dynamic simulation of the construction procedure shown was developed by the author and Mike Goodwin of Deneb Robotics, Australia.

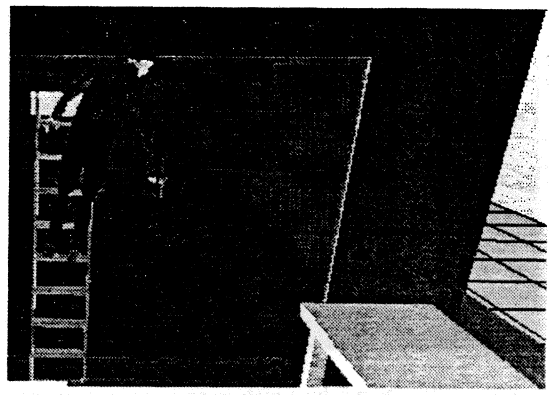

Figure 9b -A sequence from a window washing simulation

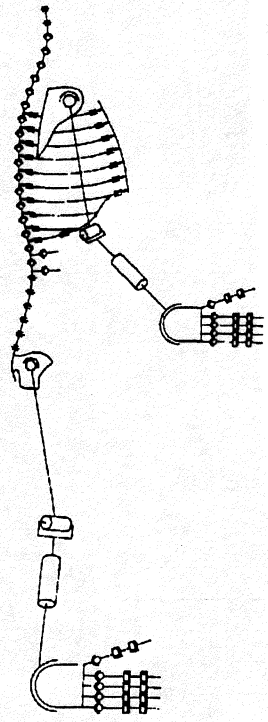

Figure 6.2 Skeleton Kinematics

12 COMPUTER INTEGRATED ROAD CONSTRUCTION

Following figure 4, an example of the use of multiple machines communicating through a shared data base is that of a fleet of asphalt paving machines in the European CIRC (Computer Integrated Road Construction project) [Peyret 1998]. In this case real time positioning equipment is used to develop a geographical information system that may be shared via radio link across a fleet of machines.

The equipment is now available commercially and Figure 10 shows a full scale road compactor equipped with driver assisted real-time radio linked display

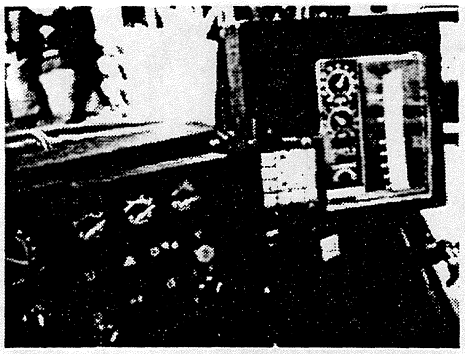

Figure 10 - On machine instrumentation system and display

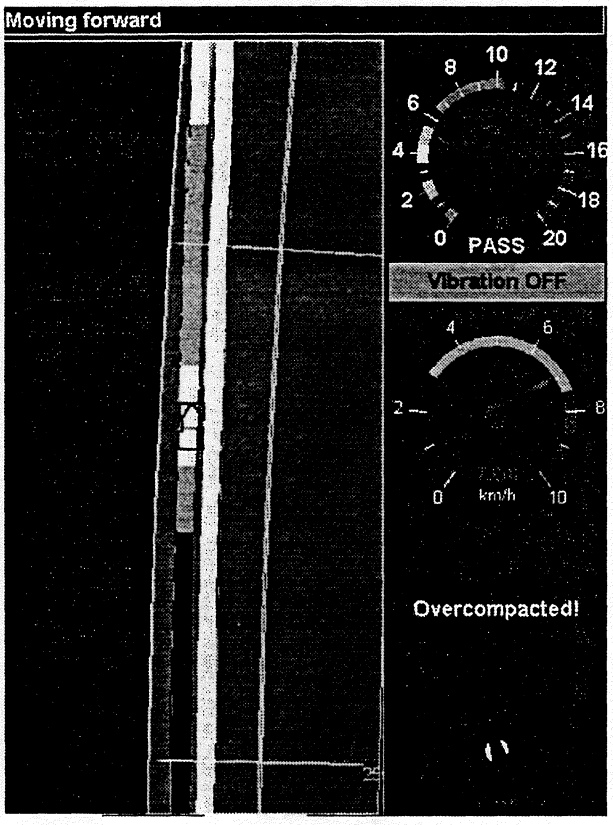

Figure 11 - Real time GIS and QA/QC system for an asphalt paving operation

Figure 11 shows the cumulative action of the compaction machine on a section of roadway, with comparison to a set of specified design procedures. The vehicle shown is controlled by a composite GPS and local laser [3D] kinematic positioning system to an accuracy of 1 cm in plan and 2 cm in elevation. The system can operate up to a speed or around 10 km per hour.

15 Conclusions

In this paper, a universal view of mixed man-machine-robot production and work systems has been presented. This view allows the design of integrated production systems wherein existing manual processes, operator controlled machinery procedures and computer controlled machinery procedures can be embraced by a single general schema. Such an integrating schema is considered necessary to permit the gradual, and appropriate, introduction of robot and automation concepts into traditional agricultural mining, construction and forestry operations. Through this integrating schema it can be seen that manual operations, mechanisation and robotic automation are developments that lie along a single continuum and that the developments merge seamlessly one into the other.

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