AUTOMATION SYSTEMS AND ROBOTIC TOOLS FOR MODULAR BUILDING SYSTEMS

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ABSTRACT

Developments in automating traditional construction methods have been fraught with difficulty. In part, this has been due to attempts at adapting conventional robotic manipulators to suit the construction environment. Robotic manipulators and construction plant and equipment have evolved from different origins and there are significant differences in the requirements of each. This paper discusses these differences and examines the underlying philosophy of construction automation systems and robotic tools. Several examples are given of prospective robotic tools for construction and one of these, a cladding fixing robot, is described in some detail.

1. Introduction

A new approach to construction automation, involving the use of robotic tools, has been proposed by the authors [1]. Difficulties encountered with automating traditional construction methods were bypassed by the use of a factory-produced parts-set. The approach is intended to de-skill as much site-based work as possible as a counter-measure against the increased shortage of skilled operatives and to reduce unit costs of production.

The use of modular building systems, in conjunction with a suite of CAD and automation tools that integrated all levels of design and construction, would introduce a high degree of structure (order) into the construction process, making the use of automation systems more feasible. A parts-set of standard components suitable for production in a CIM environment forms the basis of this new approach and has been described in [2]. More recent progress in the development of the parts-set and in the computer infrastructure needed to control design, management and construction is reported elsewhere in these proceedings. It is now possible to begin specifying robotic tools which would allow buildings to be constructed from components of the parts-set. The use of robotic tools implies that buildings would be completed quickly and more safely than by using traditional construction methods. Attention has focused on the construction of highly serviced, flexible, high-tech buildings which have simple structures of no more than two or three floors.

An integral part of this new approach is a family of automation systems (robotic tools) purposely-developed to facilitate the handling of the components of the parts-set. A number of example robotic tools are being specified as part of a feasibility study into the opportunities for robotics in the UK construction industry. Several tasks that might benefit from the use of robotic tools, specially designed for modular system building, have been considered. These include column positioning, floor laying, floor cage laying, cladding fixing, beam placing, partition placing, ceiling cage placing and floor grouting.

The following sections describe the design philosophy behind these robotic tools and include further details on the first four, with particular emphasis on cladding fixing. Thus, the objective of this paper is to report on the interim results of the feasibility study.

2. Underlying Philosophy

Robotic manipulators and construction plant and equipment have evolved from different traditions, having equally different objectives [3] [4]. Despite increasing concern in the construction industry over productivity and costs, technological change has been taking place at a much slower pace than, for instance, in manufacturing industry. The fundamental difference rests in the nature of the end-product delivered by both industries. The products of construction are more durable and are used over relatively longer periods of time [5], whilst the products of manufacturing either become obsolete or worn out over shorter periods. On-site working conditions are also different; in construction the work place is continuously changing, resulting in an ill-structured and dynamic environment. The effect of this is to impose considerable limitations on the technology and on the degree of acceptance of automation systems on-site. By comparison in the manufacturing industry, there exits a static and well-structured work environment where the work object is much smaller and is transferred from work cell to work cell. This type of production results in a structured environment with the opportunity to automate certain repetitive tasks.

Another basic difference lies in the origins of robotic manipulators, devices which began life in the machine tool industry. For them, component stiffness is an all important property in obtaining accuracy and repeatability in machining and assembly. In construction, equipment such as cranes are generally rugged, but not particularly stiff. In manufacturing, robots have a low payload to weight ratio (approximately 1:20); the ratio is much lower for a crane. The nature of loads manipulated in both industries is reflected in the different types of plant and equipment employed.

Other essential differences between the industries are their structures and work environments. The typically unstructured construction site and the nature of the end-product require that construction plant and equipment be mobile. Therefore, any robot working in such an environment will need to have sophisticated navigational capabilities, obstacle avoidance systems and sensors of various kinds. A completely automated construction device will need to be driven by sensor-based operations. Researchers in this area have found that it is extremely difficult to control the position of manipulator arms and mobile robots in an unstructured environment, and it is not clear that they even fully understand the associated problems, let alone how to overcome them [6]. Experimental work at various research centres [7] [8] [9] has highlighted the difficulties of designing machines to emulate actions which animals can achieve without difficulty.

One argument against attempting to solve these problems specifically for construction is that if one waits long enough they will be overcome by researchers in other fields anyway and can thus be utilised in construction at a far lower cost. However, the problem of construction automation is an urgent one which can be solved, at least partially, by analysing the differences between conventional robotic manipulators and construction plant and equipment. It would then be possible to make progress by marrying together the useful properties of each. While it is still not possible to effect a well-structured factory-like environment, it is possible to create a 'factory in microcosm' or work-cell in which a specialised robotic manipulator can work within a confined area before being moved on to its next work position. This could be achieved either by building a sophisticated work cell that includes several robotic tools, as in the case of the steel erection system [10] being developed in

Japan; or by adapting currently-available construction plant and equipment, as in the case of the cladding fixing robot described in section 6. A review of the applications described in the previous Symposium [3] highlighted that current construction plant and equipment is just beginning to make use of modern high-tech devices such as sensors, radio controls and signal processors which are well proven elsewhere and relatively inexpensive. The use of these devices can transform mechanical construction plant and equipment into something approaching automation.

Another objective of the research described in this paper was to design robotic tools rather than fully automated solutions using sophisticated sensor-based control systems. The tools are simple, dedicated machines that are easier to use than more generalised machines; that is, they are not aimed at solving a multitude of problems at once. At all stages of design, every effort has been made to minimise the number of degrees of freedom of the devices, thereby reducing machine costs and improving their reliability. MIT's automated shear stud welding system [11] is a useful example. The robotic tools described in the following section are intended to reduce the work of operatives, but do not eliminate them entirely from the construction cycle. It is envisaged that an operative would be on-site to monitor performance and close the control-loop. This will eliminate otherwise necessary sensors, thus keeping costs and complexity low. Even so, these robotic tools can only become economically and technically successful if their use is well planned and optimised.

3. Column Positioning System

In conventional steel frame erection processes, columns are positioned first, followed by beams. Columns are lifted by a crane and held in the vicinity of a foundation pad. Fine positioning of the column is accomplished by operatives pulling with ropes. Finally, an operative will climb a ladder or an improvised scaffold tower and release the crane's hook from the column end. The operative is very often in an unbalanced position whilst performing this task.

The proposed column positioning system has been designed to remove the operative from the vicinity of such dangerous work and to improve the efficiency of steel erection. The system consists of an automatic, remote-controlled clasp and inclinometers, and a column positioning robot (CPR) working in conjunction with a mobile crane. Figure 1 illustrates the arrangement in operation.

For automation purposes, it is proposed to use a clasp attached to the crane's hook and a pair of inclinometers mounted on the hook's pulley. The clasp would be attached to the top of the universal column by an operative. The release mechanism would be remotely-controlled and would probably be electrically operated. This automated device would thus consist of two locking mechanisms (clasps), a radio receiver, other remote control units and power supply units. A similar device has been developed by Shimizu Corporation (Japan), namely the Mighty Shackle Ace.

Once attached, the inclinometers would provide the crane operator with feedback of the deviation of the column from the vertical about two axes. Feedback signals would be radio (telemetered) back to the crane cab and displayed on a pair of conventional analogue centre-zero voltmeters. Angular deviations from the vertical of the column about the two axes through the clasp would be indicated by needle displacements from the centres. Additionally, it is proposed to provide a radio-controlled, column-positioning mobile robot for manoeuvring the lower end of the column above the foundation pad. The robot would have a manipulator arm with three degrees of freedom and a latching mechanism as its end-effector. This mechanism would be attached to the lower end of the column, allowing it to slide vertically to accommodate final positioning. Yaw motion would provide the fourth degree of freedom. It is expected that arm motions and the latching mechanism would be hydraulically operated while arm rotation would be electrically driven. The entire mechanism would work under radio control from an operator standing nearby. The robot would be tracked or have rough-terrain wheels. Its primary source of power would be a petrol (or diesel) driven engine with generator and battery for supplying all electrical power.

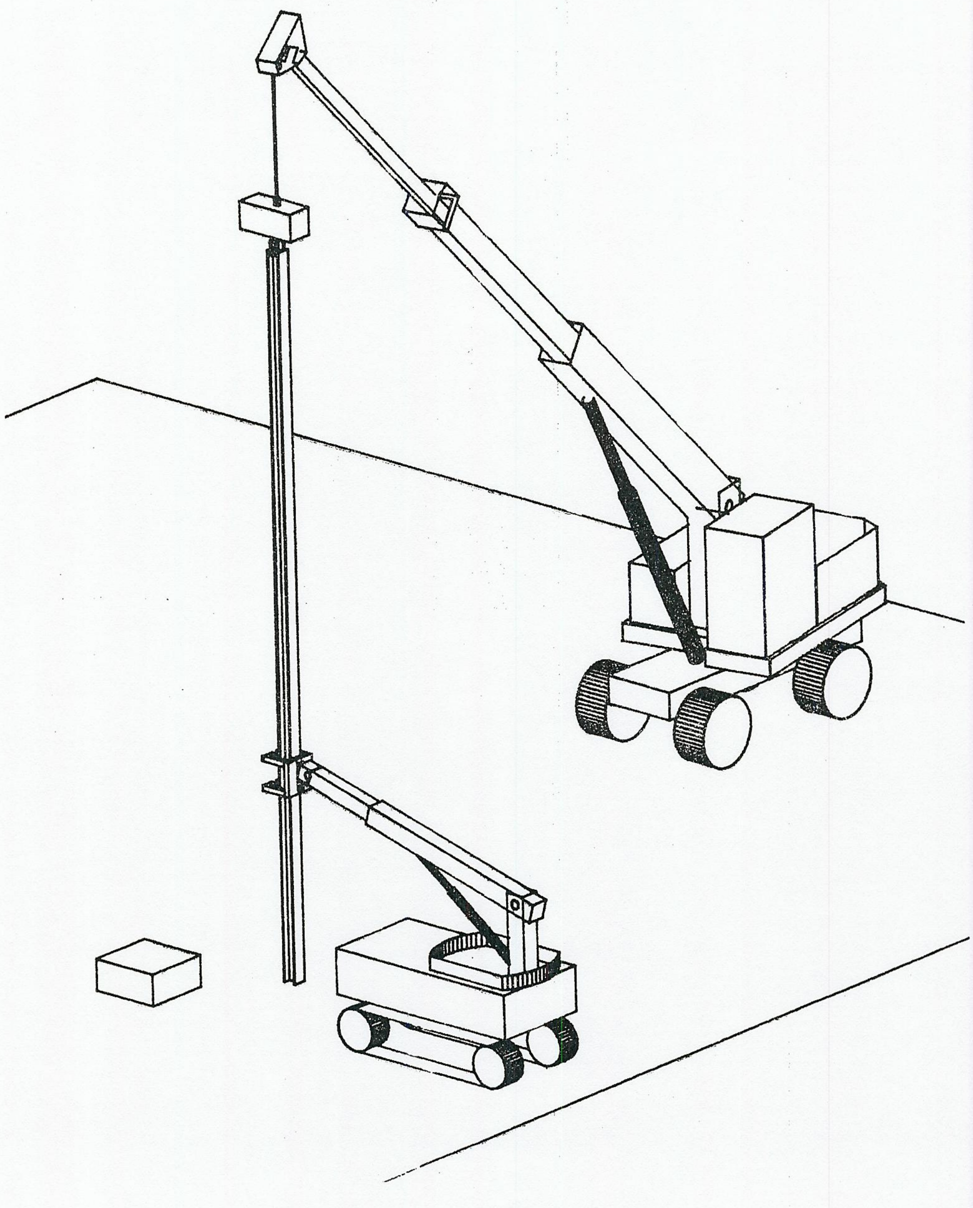

Figure 1: Column Positioning System

4. Floor Laying Robot

In conventional, insitu, reinforced concrete floor construction, floors are cast with beams on timber shuttering and left until the concrete has sufficient strength to support itself. The amount of material and labour costs in this approach led to the development of precast centering systems such as hollow beam, and plank and beam. Precast components do not require temporary support, but are cumbersome to erect in one operation.

Improvements in the load to weight ratio of reinforced, autoclaved and aerated concrete has resulted in planks that are 75% lighter than dense concrete, yet which do not compromise on structural strength. One particular manufacturer produces planks that support loads up to 6.5 kN/m^2 having a thickness of 100 mm, a span of 2.0 m and a density of 625 kg/m^3. These new types of floor planks make it possible to construct floors using prefabricated components, saving labour, equipment, time and decreasing the weather vulnerability of the operation.

The proposed floor laying robot has been designed to facilitate the handling of planks made of reinforced, aerated concrete or materials with similar load to weight ratios. The system consists of the floor laying robot and a mobile crane with operative (see Figure 2).

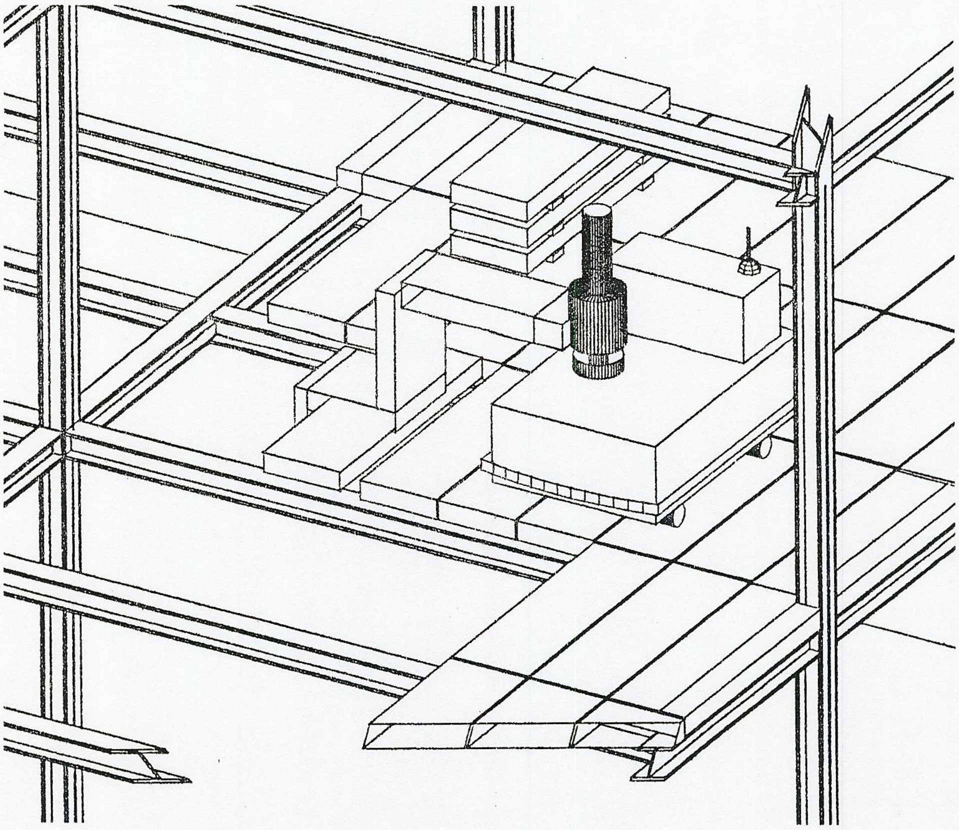

Figure 2: Floor Laying Robot

It is proposed that an initial edge path of planks would be laid using a mobile crane: the edge path would be used subsequently for storing consignments of planks. The crane would also be used to lift a mobile radio-controlled robot, designed specifically for floor laying, on to the edge path. The robot would then be operated under radio control to lift planks from the consignment and then move them into position. It is envisaged that the mobile robot would have a simple end-effector which would enable the planks to be lifted and lowered into position. In order to reduce costs, the robot arm would have vertical motion only. The extra degrees of freedom required for final plank positioning would be provided by manoeuvring the vehicle which would have steerable wheels at both ends, thus allowing omnidirectional motion.

The primary source of power for the robot would be a petrol (or diesel) driven engine with generator and battery for supplying all electrical power, although the actuator could be either electrically or hydraulically operated.

The floor laying robot requires surface sensing and obstacle detection systems to assure safe operation. Also, some means for aligning planks, with respect to those already laid, and sensors for detecting overloading on the robot would be needed. Furthermore, the clamp end-effector would require a force sensor to enable the robot to determine whether or not the plank had been correctly placed before releasing it completely.

5. Floor Cage Placing Robot

Traditionally, services have tended to be placed in ceilings where it is difficult to work, instead of putting them within the floor void where access might be easier. This conventional approach may also mean that several specialist trades are working at the same time in confined spaces and in undesirable postures. Operatives must raise large, heavy components over their heads for fixing within the ceiling void, requiring access from temporary scaffolding or platforms.

A key element in the modular approach to the construction of high-tech buildings is the use of floor cages containing all the services that are likely to be required. The raised floor system thus proposed would be made of prefabricated cages to provide a void for all the services that the floor is expected to carry [1] [2]. A hard surface, incorporating access panels, would cover the top of the cages providing a base for wood or carpet finishes. This type of floor construction eliminates the concurrent on-site installation of several services and finishes, thereby reducing the number of operatives working within the same area. It can also reduce overall construction time, improve quality control and might even be more economical.

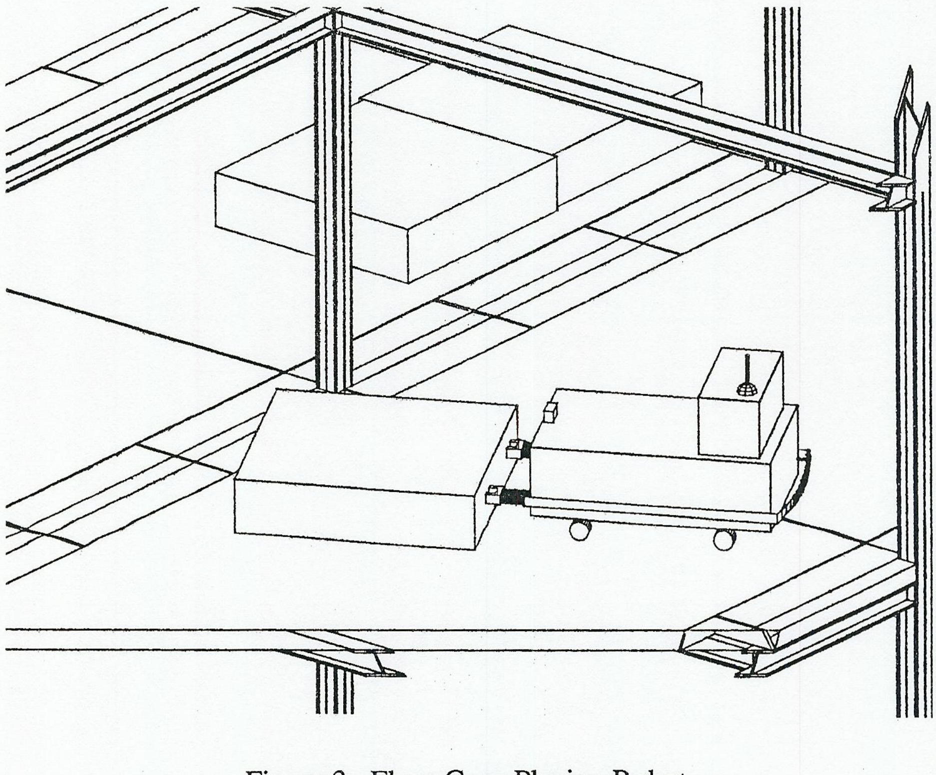

Figure 3: Floor Cage Placing Robot

The proposed floor cage placing robot has been designed to manipulate floor cages, removing the operative from handling a heavy load in an uncomfortable position and performing a monotonous task. The system would consist of a loading mechanism, an external work platform and the floor cage placing robot. Operatives would be needed for fixing the cages in their final positions, for positioning the work platform and also controlling the robot.

In order to deliver floor cages to the particular level on which they are required, it is proposed to use an external access work platform. This platform would be a modified version of a commercially-available product. The standard unit would require a ramp to be attached to it in order to unload the cages on to the working floor. For placing the floor cages on to the floor, it is proposed to use a radio-controlled vehicle. Figure 3 illustrates the system in operation.

The primary source of power for the robot would be a petrol (or diesel) driven engine with generator and battery for supplying all electrical power. The vehicle would have a latching mechanism consisting of a gripper capable of latching on to different sizes of cage and for releasing them once they are located in their final positions. The vehicle would have a high degree of manoeuvrability provided by steerable wheels at both ends.

The floor cage placing robot is thus very similar to the floor laying robot and it is possible that the same vehicle could be used for both operations by simply changing end-effectors and certain control modules.

6. Cladding Fixing System

Traditionally, external walls were constructed as loadbearing elements, using basic materials such as masonry and bricks. Today, non-loadbearing external walls are commonplace with loads transferred to the ground by means of a frame. Because external walls need no longer be loadbearing, it is possible to enclose buildings in a variety of modern materials. A 'typical' cladding system would consist of an aluminium frame to provide a modular carrier matrix, giving full support to all four sides of a cladding panel. Cladding panels can be of glass, aluminium and steel alloys, plastics and so on.

Cladding panels tend to be carried up ladders by operatives and then fixed in position. This usually involves working in uncomfortable positions which are also potentially dangerous. It is proposed to automate the placing and fixing of the cladding panels by means of a cladding fixing system, thereby removing the physical effort required by the human operator in this dangerous process and improving the efficiency of the external wall cladding process. The system consists of an external access work platform, a cladding robot and a rough-terrain, fork-lift truck.

The cladding robot has been designed to work from a modified commercially-available mobile work platform as illustrated in Figure 4. Sets of cladding panels are delivered to the stock-cradle attached to one side of the work platform using a rough-terrain, fork-lift truck. The cladding robot is rail-mounted on top of the work platform to provide horizontal movement parallel to the cladding rails. The robot consists of a manipulator arm with two degrees of freedom; lateral movement is provided via a pair of lazy tongs and angled, swivel motion. Its end-effector has pneumatically-operated suction cups which are designed to hold a single panel. The manipulator arm would be used to place and hold the cladding panels in their final position while an operator fixes them. The stock-cradle in the work platform is designed to accommodate up to four cladding panels at one time. The panels may be up to 1.60 m x 1.80 m in size with a maximum weight of 100 kg.

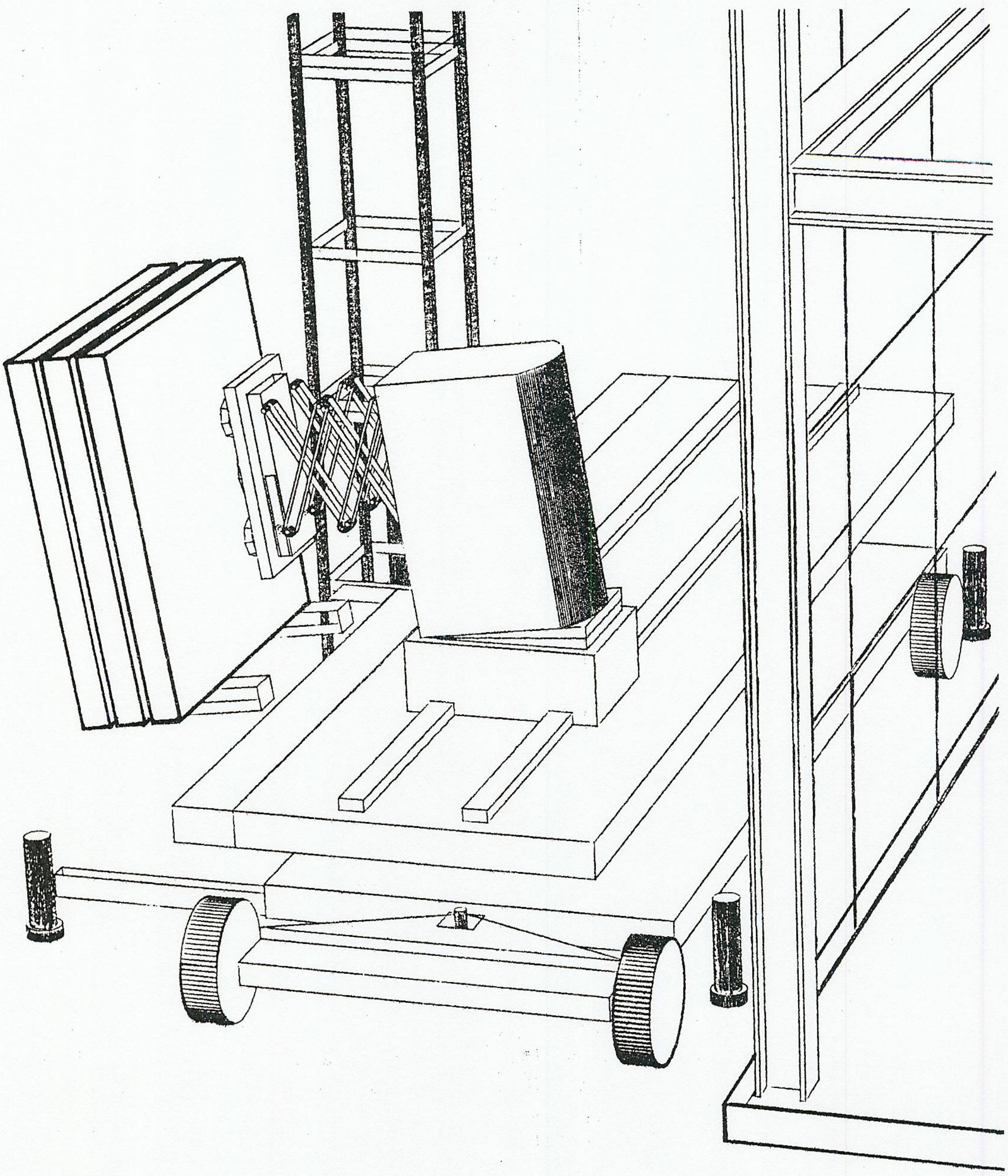

Figure 4: Cladding Fixing System

Once the work platform has been loaded it is then raised to the required level under operator control. The robot is now ready to commence its task, part of which can be fully automated to create a factory in microcosm or work cell. The operator would signal the robot to locate itself in front of the cladding panels stored in the stock-cradle. The manipulator arm of the robot would move forward until the end-effectors were in close contact with the cladding panel. Detection of contact would activate the suction cups to pick up the panels. The manipulator arm would move backwards and the angled, swivel motion would move the panel from its previously angled position to a vertical position facing the cladding rails. The lazy tongs of the manipulator arm would now push the panel towards its final position. The operator would then take over command using a pendant control which would command the robot to move the panel into its final position. The operator would be standing on a floor within the building in close proximity to the panel, but in safety. When the desired position of the panel has been reached, the robot would hold it in place while the operator secures its temporary fixing. The operator would then signal the robot to release the suction cups. It would then automatically proceed to pick and place the next panel. This would, of course, involve some motion of the robot along the cladding rails. Such an operation would be performed under automatic preprogrammed control. Cladding fixing would continue along the length of the platform which itself can either be raised to the next level or moved along the building to its next reference position.

The type of forces applied by the manipulator arm to move the cladding panels implies that it would need to be hydraulically driven. Safety is a fundamental concern, due to the height at which the task is performed and the nature of the manipulated components. A sliding guard to bridge between the work platform and the building would be mounted at the bottom of the work platform. The guard would act as a safety barrier in the event of malfunction of the manipulator and release of the panels from the suction cups. The robot would also have a obstacle detection sensor, particularly when it swivels around and moves along the work platform.

The primary source of power for the robot would be a petrol (or diesel) driven engine with generator and battery for supplying all electrical power.

7. Conclusions

By redefining certain basic methods of construction it is possible to develop a family of robotic tools which are matched to those methods. In proposing robotic tools, it is important to identify the essential differences between conventional, robotic manipulators and construction plant and equipment and then to marry together the most desirable features of each. By such means it is possible to create a factory in microcosm or work cell in which simple robots, under a combination of operator and programmed control, can speed up, simplify and make safe otherwise laborious and dangerous tasks. The robotic tools described in this paper are simple, purpose-built devices that employ existing technology. Further details are described elsewhere [12], although are not yet completely specified. It is the intention to develop the cladding robot in more detail using simulation techniques in order to achieve an optimal configuration prior to detailed design.

8. Acknowledgement

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