HEROIC: A CONCEPT ROBOTIC SYSTEM FOR HYDRO-EROSION IN CONCRETE REPAIR PREPARATION

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Abstract:The definition of the excavation geometry in concrete removal has a considerable effect on the longevity of the subsequent replacement repair material. Also, when removing defective material, it is important to use methods that do not cause micro-cracking and other structural damge.The hydro-erosion concept, a controlled version of hydro-demolition, represents a means of excavating material to well definded gometry without causing such damage.To achieve a robotic solution for this, it is necessary to incorporate sensing and control strategies that are roboust in the harsh environment. An experimental robot has been devised for investigations into these issues. This work is being undertaken within a European Community project named HEROIC: Hydro Erosion for Repair Of Insitu Concrete.

Keywords: HEROIC, concrete, repair, hydroerosion, robot, sensing, control

1 INTRODUCTION

There is an increasing demand for concrete repair in the developed world. This affects highways, bridges, buildings, factories, power stations, airports and coastal defences. The scale of this is indicated by the estimated 3 million kms of paved highway, 4.4 million dwellings in system buildings and 900,000 bridges in the European Community alone. In the reported research the objective is to advance the use of hydro-erosion systems for removing defective concrete prior to the placement of replacement material.

Achieving timely, long lasting and low-cost repairs is therefore extremely important. Equally important factors are worker safety and protection of the natural environment. Effective use of non-destructive testing methods (NDT) that gives an accurate assessment of structural condition can take advantage of censor fusion techniques. This can give a basis for setting priorities. Longevity of concrete repair work is frequently not achieved, with repairs lasting perhaps only one or two years. A major question here is whether or not the actual repair process causes accidental damage. Also, it is known that repair design has a great influence on durability.

As usual, in the field of automation and robotics for the construction industry, the potential of high cost needs to be evaluated against alternative manually operated alternatives. Regarding safety with erosion, which involves the use of high-pressure water, there are compelling advantages in remote handling of tools, which also gives the way for significantly higher capacity systems. Also, where a suitable access solution can be achieved, there is the possibility for process containment.

HEROIC is a European Commission supported industrial research project No.BES2-2783, under the CRAFT BRITE-EURAM programme. It commenced in September 1998 and is due to finish in August 2000. HEROIC stands for Hydro Erosion for Repair of In-situ Concrete. The scope of this includes NDT based prediction of the repair task, control feedback for automation of the hydro-erosion process and robotic tool handling systems. The sequence of these is followed in this paper.

2 REPAIR PREPARATION

2.1 Concrete deterioration

There are many causes of concrete deterioration, a topic covered extensively elsewhere [1]. Apart from earthquake and accidental loading, causes of deterioration include acid rain, chloride contamination, and chemical attack. In some cases, the presence of sub-standard materials, poor design details and lack of production quality control aggravate this. Low in-situ strength, lack of protective cover to reinforcing steel and ineffective dispersal of rainwater dispersal are typical defects. At an advanced stage of deterioration, expansive corrosion of the embedded reinforcement steel can cause cracking and spalling of the concrete, leading to reduced structural capacity and durability. The repair preparation work addressed in this research concerns the controlled removal of defective concrete and exposure of reinforcing bars, typically in the 75 mm to 200 mm depth range.

2.2 *Principles of the hydro erosion method*

The name, Hydro-Erosion, has been adopted as a more appropriate description of what is otherwise understood to be Hydro-Demolition, a process by which a high-pressure water jet is applied to cutting and removal of concrete. It reflects the main research objective, to control the process to a degree not previously possible.

Whilst no explanation has been found in the literature, it seems probable that the water jet removes material by a combination of actions, crushing of microstructure, shearing and the explosive action of pore water pressure. In tests conducted so far, it appears that the erosion power (removal rate) depends on the hydrodynamic force delivered at the nozzle in relation to the strength of the concrete being eroded. Aggregate grading has some influence in terms of the maximum size of aggregate, mixes with smaller maximum aggregate size tending to be more resistant to erosion. This might be explained by comparing the surface area/volume of large and small particles. Smaller stones have potentially more bonded surface and, therefore, ought to be more difficult to dislodge.

The hydrodynamic force at the nozzle (nozzle force) is a function of the operating pressure, flow rate and nozzle parameters. At two extreme limits, a manual system would typically operate at 20 litres/min at 1800 bar or 60 litres/min. at 400 bar. In general, it is more effective to increase flow rate than pressure. On account of the limited allowable body force for manual handling, a tool would need to be mounted or remotely handled where high flow rates and pressures are to be employed.

2.3 *Erosion design*

The quality of the excavation geometry is an important factor for the longevity of the subsequent material replacement. In particular, excavations should have good boundary definition, stepped rather than feathered at the edges, with irregular patches removed to well defined rectangular shapes. In order to achieve this regularity, it will typically be necessary to remove higher strength concrete at the boundary. Figure 1 illustrates a typical design.

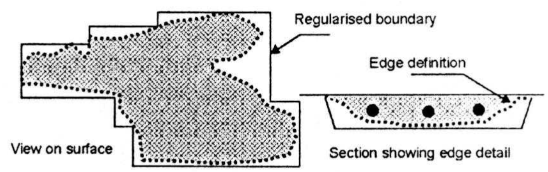

Figure 1. Excavation design

The result of uniform water jetting at a fixed setting would tend to produce an 'excavation to strength', this corresponding to the dotted line shown in figure 1. Whilst it can be argued that this is corresponds to a correct procedure, one that gives selective remove of material falling below a required strength, it can result in poor geometric definition and excessive depth removal. In extreme cases the latter may compromise the residual strength of the component.

Achieving the design illustrated in figure 1, clearly involves the remove of some higher strength material at the boundaries i.e. 'excavation to depth and form', which can only be achieved by varying the erosion effort over the surface. This could imply the need for varied nozzle force or prolonged application.

2.4 *Advantages of method*

Hand chisels and powered percussion tools are traditionally used in braking out concrete. Compared with these, hydro-erosion offers a distant advantage in that its power is highly concentrated and continuous. In the case of powered percussion methods, which are pulsating rather than continuous in delivery, there is evidence [2] that a region of micro cracking can occur some distance away from the impact zone. European Commission CEN/TC 104/SC 8 N 439 draft document (relating to concrete repair preparation) confirms this point, acknowledging that "hydrodemolition is a fast and effective way of removing concrete"[3].

Other advantages are that the prepared surface is left free of all loose particulate matter, with the back-side of the reinforcing steel cleaned by the abrasive action of the removed debris. Salts and other contaminants will also tend to be washed out during the process. Depending on the operating settings, non-tightly adhering corrosion can be removed with the water jet. Unlike with powered tools and dry abrasive blasting, which is also employed for concrete removal, hydro-erosion is dust free.

Depending on the system capacity and settings, water jetting, the basis of the hydro-erosion method, can also be used to cleaning stone, brick and metal surfaces, raking out mortar joints, removal of protective coatings to steel work, widening cracks in concrete prior to filling, for examples.

2.5 *Equipment selection*

There is a wide range of water jetting equipment both for manual, mounted and remote handling applications. The commonly accepted classification is according to the range of nozzle pressure, as given in table 1. This data is of limited value, however, because, as previously discussed, the nozzle force is also dependent on the nozzle diameter and flow rate. Abrasive jetting, which is included in table 1, refers to systems where abrasive particles are included into the water jet for applications such as cutting steel sheeting.

Classification	Pressure Range (Bar)
Pressure jetting	Up to 700
High pressure jetting	700-1700
Ultra-high pressure jetting	1700-2700
Abrasive jetting	1000

Table 1: Classification of water jetting

Equipment intended for manual handling can be operated at higher nozzle forces than permitted, by the use of a mounting arrangement, for example, a swivel clamp for mounting on scaffolding. For high capacity erosion, however, adoption of some form of remote handling is inevitable.

3 STATE OF THE ART IN REMOTE SYSTEMS

A number of automatic and robotic hydro-demolition systems have been developed for a range of applications. The common approach is a tool head that gives local, single axis motion for the nozzle lance within a protective casement, with some systems also pivoting and gyrating the nozzle lance. Other systems adopt a smaller format with multiple nozzles that rotate. The main differences are apparent in the methods of delivering the tool head to the work face. For dam wall applications, suspended wire access has been used, for example. In the case of road and bridge repair, robotic systems of the type shown in figure 2 are becoming more widely employed. The system illustrated in figure 2, which is produced by NCC, Sweden, can deliver 80 litre/min at up to 2500 bar using a 3mm-diameter nozzle. Depending on the quality of the concrete being removed and the configuration of the machine, removal rates of 0.5 cu.m per hour are achievable with this system.

The performance of robotic hydro-demolition systems can be judged according to their ability to satisfactorily complete the set tasks of the Swedish Standard [4]. For this, the equipment is required to complete an 'excavation to strength' task in three passes, with fixed system setting in terms of nozzle force and feed rate. A specially prepared, 1200mm x 1200mm x 300mm reinforced concrete trial slab is provided, which is cast in two stages, the lower concrete having 20N/mm^2 greater strength than the upper concrete. Steps are cast in the slab to give a range of depths for excavation. To pass the test, the system must remove all the low strength concrete, achieving surface definition and profile to within specified limits. The test piece geometry and a typical result are shown in figure 3. Laser scanning is used to evaluate the achieved surface topography. Any subsequent modification to equipment necessitates re-testing. This is the only construction industry standard that the authors are aware of.

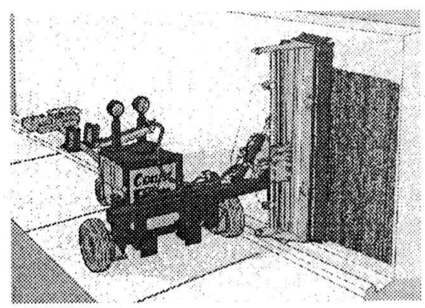

Figure 2: Robotic system (NCC Sweden)

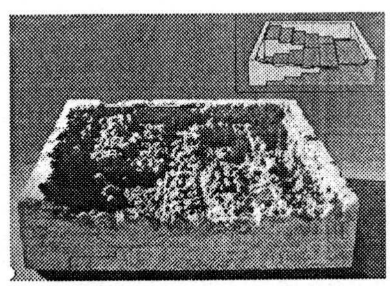

Figure 3 Swedish hydrodemolition certification

4 THE HEROIC PROJECT

4.1 *Industrial objectives*

The industrial objectives of the HEROIC project are to establish the 'know-how' for advanced automatic and robotic delivery of hydro-erosion as a controlled form of hydro-demolition. Targets for this are:

- Predictive modelling methods based on inspection and NDT data.

- System control technology that uses the sound and vibration of the hydro-erosion processes.

- High definition, excavation geometry.

- Productivity, quality control, worker safety and environmental protection.

4.2 *NDT based prediction*

The decision to make a repair can depend on many factors. Apart from the obvious need for repair associated with excessive loading or distortion, the decision for repair relies on visual observations, NDT procedures and material sampling. The latter are, by implication, destructive. They are also expensive and time consuming to obtain and evaluate and are, therefore, usually limited in number.

There is a wide range of NDT devices, each quantifying a particular mechanical or electro-chemical parameter that is deemed to indicate the condition and life expectation of the concrete-steel composite. They address the need to quantify parameters such as reinforcement diameter, size and spacing, insitu concrete strength, voiding, cracking and structural integrity, level of electro-chemical activity and rate of reinforcement corrosion.

Well-established devices are the metal (rebar) detector, rebound hammer, half-cell, ultra-sound and pull-off unit. Each of these has unique accuracy, repeatability, reliability and relevance characteristics, the latter referring to the degree to which they actually reflect the intended condition parameter. Whilst some work has been carried out to quantify this, gaps remain in this performance data.

To improve the value of NDT and, to a certain extent, emulate human intelligence in inspection work, the application of sensor data fusion techniques are being investigated. However, whilst the expectation might be for a single binary outcome i.e. repair or not repair, achieving this is not a straightforward matter. They each address a different aspect of the condition, in some cases giving incompatible quantities, for example, voltage vs distance. Pulling back from the realms of artificial intelligence, implicitly necessary for the binary outcome, a practical approach can be using a data processing tool that allows operator 'what if' investigations with the gathered data. By this means, the effect of downgrading the influence of individual NDT methods can be investigated, for example.

Data fusion models and their implementation for prediction of the hydro-erosion task effort are currently being worked on in the study. Figure 4 illustrates one of the models under investigation Using such a tool, contractors will hopefully be better able to estimate the plant and production time requirements, for example. Because the data is collected on a well-defined grid, video captured visual data can be included in the fusion model. Figure 5 shows a typical data collection grid and the results of applying image-processing techniques to defective regions of a concrete wall.

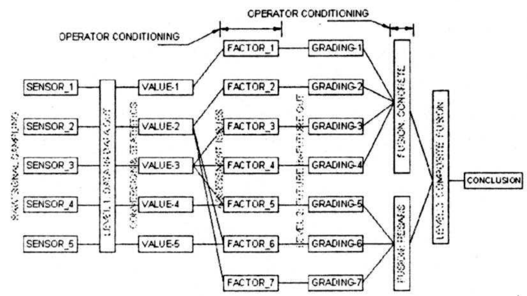

Figure 4. Sensor data fusion model

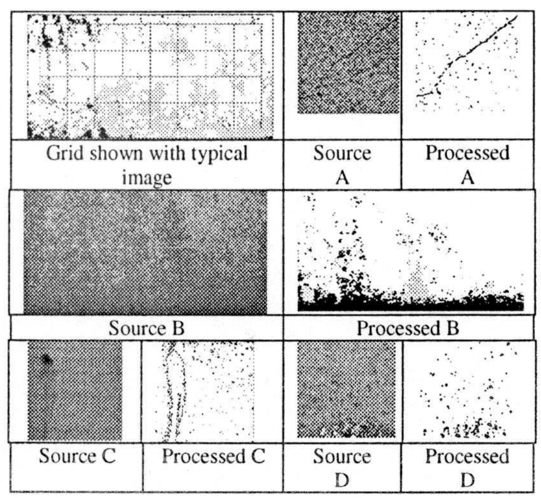

Figure 5. Application of digital image capture in sensor data fusion

4.3 *System performance criteria*

With the technology fully worked out, it should be possible to achieve an accurate excavation in a single pass, with the nozzle force and its dwell time varied according to the progress of material removal. This follows the 'excavation to depth and geometry' approach rather than the 'excavation to strength' approach embraced by the current Swedish Standard. Over-excavation of material, which can lead to unacceptable loss in residual strength, is thus avoided. A further advantage is that remote operations will be more practical, particularly in situations where a visual line on progress is difficult or dangerous to maintain. The quantified performance objectives for the HEROIC system are:

- The control system must delivery consistent accuracy in the excavation over areas for which the concrete strength varies between 10 N/mm^2 - 50 N/mm^2. The accuracy of the excavation depth is to be +/- 6 mm.
- Where zones of abnormally low strength (less than 10 N/mm^2) are anticipated, the control system must perform similarly to above.
- For reinforcing bars running parallel to the surface, their position and direction must be detected at the stage where more than 6 mm of their diameter is exposed in the excavation.
- It must be possible for the water jet to follow the centre-line of an individual, parallel to surface, bar to within 1/3 bar diameter and ensure that no concrete remains adhered to it.
- The clearance behind fully exposed reinforcing bars is to be controlled to within +/- 6 mm.
- Reinforcing bars that are not parallel to the surface shall be detected when they are exposed.

The extent to which these can be achieved depends largely on the success of the sensing methods currently being experimented.

4.4 *Harsh environment*

The environment in the region of the nozzle is probably one of the worst imaginable. Apart form the presence of water, high humidity and near zero visibility, the energy of the eroded debris, which comprises a range of abrasive particles, is extremely high. This is confirmed by the high wear rate of metallic components in the region of the tool. With this in mind, there is no scope of conventional real-time sensing.

4.5 *Sensing*

As previously stated, system noise and vibration are being investigated for monitoring the erosion process. Figure 6 illustrates the experimental sensing head that is mounted on the nozzle lance. It gathers vibration and noise signals, which are feed to a dedicated, high frequency analyser.

4.6 *Man machine interface*

Effective design of the man-machine interface is crucial to successful operation and commercial take up robotic technology. Existing interfaces vary considerably in sophistication, those provided for hydro-demolition robots typically comprising switches and joysticks. With the possibility of the feedback currently under investigation, this would clearly need extending in some robust manner. Whilst the experimental system has a VDU display for presenting a map of the erosion process, use of coded noise feedback is under consideration, because this could be more robust for the on-site application.

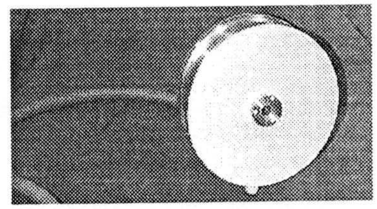

Figure 6 Hydroerosion sensor head

4.7 *Tool Delivery*

The issue of access plays a role in productive use of any tool in the concrete repair industry. Also if tool delivery is expensive or elaborate then on-site acceptance of the new technology will be low. Moreover, the required access strategy must be flexible and robust, in order to cope with the large variety of hydro-demolition scenarios. Currently, a two-stage tool delivery system is envisaged, this consisting of a standard access platform and a robotic manipulator, which is remotely operated by the user. The required flexibility combined with low-cost and robustness represents a major challenge for the HEROIC consortium.

4.8 *System control*

The main task in the HEROIC project in the area of control is the acquisition and analysis of the acoustic signature of the hydro-demolition process and application to controlling the hydro-demolition process. This acoustic signal will be used to detect whether rebars are exposed and to what depth. Some attention will be given to diagnosis of the state of the nozzle. The control system envisaged must not provide accurate resolved motion or control of the water pressure or flow. Instead, a feed-rate strategy is necessary, where the nozzle is moved quickly over areas with sufficient erosion and slowly over areas still be eroded. The main challenge will be create a robust control system that will be able to cope with all eventualities.

4.9 *Safety and pollution control*

As a manually handling method, hydro-demolition is a potentially dangerous for the worker. Clothing and human tissue are easily cut by the high-pressure water jet. Sustaining the nozzle force leads to strain with prolonged use and the accompanying high level of humidity is uncomfortable for the operator. A further hazard, which the authors are not aware has been investigated, is the unknown consequence of inhaling fine particles that are entrained in the water vapour. In areas where water jetting has taken place, calcified deposits are found, presumably associated with the re-activation of removed cement.

With automatic and robotic systems, which typically can deliver 50-100 litres/min, a considerable volume of vapour is produced. Once the process has started, and the uneven topography developed, it is impractical to seal the tool to the working surface. However, it should be possible to capture the vapour through the use of suction equipment. This is one of the points of investigation in the project, an environmental protection measure for workers and the local environment.

4.10 *Access*

In most cases, it is appropriate to deliver the tool head by means of robotic manipulator of the type illustrated in figure 2. However, where the process is to be delivered in situations involving difficult or dangerous access, weight is an important issue. The maximum allowable weight for individual manual handling is 25 kg. For this reason, a modular approach is under investigation by which manageable sub-systems can be delivered to the point of assemble.

5 EXPERIMENTAL ROBOT

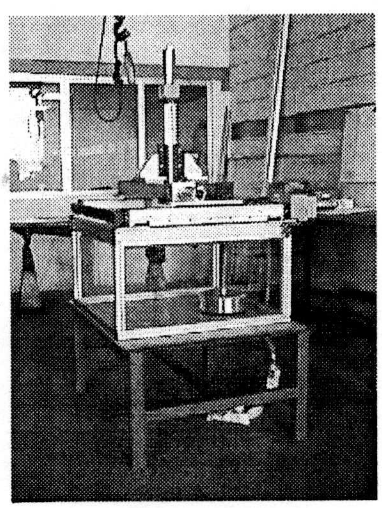

Figure 7. HEROIC experimental hydro-erosion robot

An experimental robot, illustrated in figure 7, has been developed for remote tool handling and sensing investigations. It has three cartesian motion axes with a working envelope of 600mm x 600m x 200mm. It has an interface the gives a range of operator feedback for the progress of the hydroerosion task. A range of reinforced concrete test pieces have been produced for erosion trials with it. These has been designed to represent typical reinforcement detailing of columns, floors, walls and bridge decking.

6 CONCLUSIONS

The background to hydro-erosion has been presented together with the HEROIC project objectives. Whilst existing automatic and robotic system 'excavate to strength', a selective approach for the removal of defective concrete, there is the need to produce good geometry in order to make repairs last. This 'excavation to geometry' approach requires the system to alter its cutting power parameters or dwell time (extended application on higher strength areas). The HEROIC project aims to establish sensor and control technology that will make possible such real-time control of the erosion process. In this, advantage is to be taken of inspection and NDT based prediction of the condition and insitu strength of the concrete component.

On the lines of the Swedish system for hydro-erosion certification, there is scope for certification more appropriate to 'erosion to geometry'. An appropriate approach might be to provide, for example, a polygon or elliptical shape patch of weak concrete to two depths within a slab. The certification requirement would then be for an encompassing rectangular excavation within allowable tolerances of depth, surface profile and edge detail.

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