1. Introduction

The developed world faces a growing crisis in the preservation of its built environment. Owing to the so-called “concrete cancer”, which is associated with acid rain and other agencies for decay, there is a multi-billion ecu accumulating annual need for repair in all manner of concrete structures in Europe, alone. This affects highways, bridges, buildings, factories, power-stations, airports and coastal defences. The scale of this is indicated by the estimated 3 million km of paved highway, 4.4 million medium/high rise system built dwellings and 900,000 bridges. Removal of defective concrete, and replacement with protecting materials, represents a significant part of the ongoing repair and maintenance of these.

Hydro-erosion is a process by which defective concrete and other construction materials are removed under the action of a high pressure water jet. Material removal is achieved by the focused action of the small diameter water jet, which typically delivers 25-40 litres/min, at pressures in the range of 700-1,000 bar. Increased erosion power can be achieved by increasing the flow rate or pressure. While low flow rate systems can give highly desirable reduced waste volume, they are, unfortunately more sophisticated and expensive to produce.

The method is most commonly operated with hand-held tools, although a few mechanised systems have been produced. While the latter promise significant advantages over hand-held tools, the lack of sensor driven control know-how currently acts as a brake on realising these benefits. If a reliable technology can be established, then improvements in productivity, quality control and worker safety can be realised.

Through anticipated commercialisation of the research findings, a significant increase in productivity is anticipated from adoption of a sensor based control system, which uses material property predictions and the sound and vibration of the hydro-erosion processes. To date, a feasibility study has been completed, which addressed the extreme technical risk areas in the innovation. Overall, this indicates that it should be possible to achieve the control objective. Although for a substantially reduced
power water system than commercially employed, the research indicates that process sound and vibration are diagnostics for essential issues such as the exposure of reinforcing bars and malfunction of the water jet nozzle. Sensors have also been investigated for predictive modelling of the erosion process.

The quality of the shape definition of the material removal is known to affect the longevity of the subsequent repair. This means that both good and defective concrete needs to be removed to achieve a prescribed excavation geometry. With suitable feedback on the process of concrete removal, it would be possible to vary the erosion effort to achieve “excavation to shape” rather than “excavation to strength”. Figure 1 illustrates the difference between these. For automation, the principal shortcoming of the latter is that a uniform application rate of the jet produces islands in regions of high strength concrete, and over-excavation in regions of low strength concrete.

The intended automation system would enable the necessary selective erosion effort according to sensor feedback and, at the same time, protect surrounding materials and components from the accidental damage that commonly arises with other removal methods. It will also be safe for the operator, who will no longer have to handle strain inducing tools or remain at proximity to potentially hazardous equipment.

2. Industrial objectives

Regarding the industrial needs, the performance objectives adopted for the study are as follows:

- Where zones of abnormally low strength (less than 15N/mm²) are anticipated, the control system must perform similarly to the above.
- For reinforcing bars running parallel to the surface, their position and direction must be detected at the stage where more than 6mm 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 one-third bar diameter and ensure that no concrete remains adhered to it.
- The clearance behind fully exposed reinforcing bars is to be controlled to within ± 6mm.
- Reinforcing bars that are not parallel to the surface will be detected when they are exposed.

3. Developments to date

While there are a number of ways to remove defective concrete patches, hydro-erosion is the only method that carries negligible risk of accidental damage to the main body of concrete or exposed reinforcing steel. It contrasts well with traditional, powered percussion tool methods, which are prone to induced micro-cracking in the region around the repair site. For this reason, the method has been cited in a concrete repair standard currently being prepared (Emmons, 1994). It has the further advantage that high-pressure water tends to wash out chlorides and other contaminants that degrade reinforced concrete. Also, because of the focused effect of the water jet, excavations with good boundary definition are feasible. The latter is particularly important for longevity in the subsequent repair (CEN, 1997). The proposed technology will overcome technical limitations that currently make the use of hydro-erosion impractical for many types of concrete repair work. These are principally the inability to control the process automatically, making close operator surveillance necessary (highly dangerous), and low productivity because of discontinuous patterns of work. The latter is associated with the need to make multiple passes to correct the tendency to produce island/depression areas.
Currently, hydro-erosion is predominantly a hand-tool method and thus, in common with other labour with heavy tools, carries a high risk of strain induced injury (Everett, 1994). Furthermore, the current maximum legal reaction force of 250N (25kg) for workers in the construction industry dictates the use of a small capacity nozzle. For this not to be exceeded, a two to three man team can typically erode a total of 0.3m³ of concrete in a 10hr working day, operating a tool with a flow rate of 40 litres/min at a pressure of 700 bar (Rentajet, 1995). An increase in pressure or flow rate, necessary to increase the excavation rate and thus productivity, would directly lead to the permissible reaction force being exceeded. However, a robotic system could have a substantially greater payload, thus enabling more powerful tools to be delivered to the work face. Through assisted tool handling, it has been shown that productivity can be increased by a factor of five (Twigg, 1994).

While not widely employed, automatic/robotic machines have been developed within the European industry (BFG, 1996; Byles, 1997). These all depend on pre-setting parameters such as offset distance, water pressure and flow rate, and nozzle traverse rate, in an attempt to produce the required depth of excavation. Methods for achieving this are detailed in patents (Anderson and Anderson, 1996; Muller and Rath, 1986). Where the concrete strength varies, as is commonly the case, inspection and multiple passes are necessary to achieve boundary definition and uniformity in the excavation depth. Through the use of process monitoring sensors within a robotic system, a variable effort, continuous process should be possible, however.

Currently, the most technically sophisticated automation solution with hydro-erosion has been produced in Japan, for dam construction work (Sakou and Ezawa, 1995). This is mounted beneath a vehicle used to expose the stone aggregate of green (new) concrete to provide mechanical interlocking between subsequent layers of concrete. This employs a database of optimum cutting conditions for the removal of the concrete and uses an electromagnetic device to control nozzle offset relative to the embedded layer of steel reinforcement. The knowledge of the concrete’s strength is used to advantage in this solution; however, this does not deal with the essential exposure of bars for repair work.

Where cutting (concrete and reinforcing steel) rather than concrete erosion is required, grit can be added to the water jet. This, however, cannot be used in concrete erosion due to the risk of damaging the steel reinforcement. Equipment involving robotic handling of the abrasive cutting head has been used to cut off obstructive reinforced concrete piles (Kohashi et al., 1996). Here, vibration sensors were used to detect material removal, nozzle blockage and break-through, operating on the frequency spectrum in the 1-3kHz band. In EC funded research (THERMIE, 1992), acoustic and ultrasound output has been used to determine the efficiency of underwater abrasive jet cutting of nuclear waste materials.

In reported research (CRAFT, 1997), the use of vibration and acoustic output has been investigated as a possible method for closed loop control of automatic hydro-erosion equipment. Nozzle vibration is found to relate to cutting efficiency and the acoustic output to the depth of erosion. With acoustic output, it is also possible to detect the presence of exposed reinforcing steel.

The main development proposed here is the use of sound feedback for the control of the hydro-erosion process in respect to the excavation depth and exposure and preparation of the reinforcing steel. This would overcome the main barrier to high productivity through automation, namely, the inability to produce excavations automatically to defined geometry other than by continuous operator intervention. Unlike existing automation, the new method will achieve excavations to optimum shape designs, irrespective of local variations in concrete strength. This will enable the quality of boundary definition that is crucial to longevity in the repair. A further contribution is the possibility for optimisation of the excavation process through combined use of non-destructive testing (NDT) based predictive modelling and sensor feedback. Substantially increased productivity is anticipated through the ability to operate at high flow rates and pressures, in a uninterrupted, single-pass fashion.

4. Sensors for hydro-erosion prediction

For the total system, there are three separate requirements for sensing; prediction of the
erosion process, run-time feedback for process control and quality control at the post-excavation stage. This paper deals with the first of these.

4.1 Process prediction
Commercially available NDT sensor systems have been adapted for the prediction task, with a data fusion model applied to yield a single condition parameter. In the trials, the Cartesian robot illustrated in Plate 1 was used to handle NDT probes over a 1m² surface area. The precise positioning (better than ±1mm) of the probes, made possible by the robot, was found to add considerable value to the survey in terms of speed, accuracy and data flow. Reflecting the nature of the principal factors in reinforced concrete deterioration, and the need to contain the extent of the survey activity and ensuing data volume, the selected NDT systems are:

- metal detection for determination of reinforcing bar location, direction, diameter and embedded depth (known as “cover”);
- impact echo for detection of planar delamination, voids and density abnormalities (relates to strength); and
- rebound hammer for indirect estimation of shallow strength (to about 50mm depth).

4.1.1 Reinforcement detection by covermeter
Determination of the depth of reinforcement bars is a particularly important part of the erosion task prediction, mainly because it is necessary to expose completely the top layer of bars in order to make a satisfactory repair. Plate 2 illustrates a typical hydro-erosion preparation, exposure of the steel reinforcing bars clearly apparent.

Figure 2 illustrates a covermeter (Carino, 1993) employed in the robotic handling trials. This is a polarized eddy current device. The probe, which weighs 0.4kg, is designed to be hand-held. Stated accuracy is better than ±2mm or ±5 per cent (cover with assumed bar size) for commonly occurring reinforcing bar content. With an experienced operator, productivity is typically 1m²/hr for a full map of direction, center, cover and diameter. While the probe voltage is indicated on the host unit, it is also available as an analogue signal for interfacing with other systems.

Because the dielectric constants of concrete and air are of the same order, in relation to the steel, it is sufficient to know the offset of the probe from the work surface, rather than maintain surface contact. Furthermore, whereas the human operator has no choice but to keep the probe on the surface, the robot is free of this restraint. This is a significant point because possible high frictional forces and collision risks may be avoided, overcoming the need for force control. However, as in remote handling of all probes, some force limiting measure is advisable for protection of the probe, robot and structure. For planar surfaces, XYZ Cartesian motion and Z axis jaw (normal to surface) are the minimum manipulation requirement.

Using the robot, the probe head was deployed to assess the implications for remote handling. Its digital voltage was relayed to a PC-based data logger. Various combinations and arrangements of reinforcing bars were investigated in air to enable accuracy assessment. These trials addressed two issues:

1. location of bars in the XY work plane;
2. estimation of bar offset (equivalent to cover determination) and bar diameter.

A 1m × 1m mesh of 12mm diameter bars at 150mm pitch was prepared and set in the
horizontal plane. The robot was located over this with its XY axes plane approximately parallel. Maintaining the Z axis at a constant position, the probe was driven on the XY axes and rotated on the Z jaw axis until the central area of the mesh was detected. Using the grey scale representation of the signal strength illustrated in Figure 3, the position and intersection points of the bars were resolved (front/rear bar also). Fixing the bar diameter (12mm), and applying image processing techniques, resulted in the typical images shown in Figure 4. The spacing of the bars at mid-intersection points was accurate to ±2.5mm. Scanning speeds in profiling were in the 100mm-150mm/sec range. While not determined for the particular probe setting, the useful maximum scanning speed would depend partly on the pulse rate of the covermeter system.

Using the robot, the mesh was completely detected in under 15 minutes, with bar centres located to ±2mm accuracy. With fully automatic processing of the data, this time would be reduced. An experienced user of the equipment took approximately 35 minutes to completely detect and plot the mesh, locating the bar centres to ±4mm accuracy.

In manual handling, the detection of bar size and depth is achieved by taking readings using both sides of the probe, the internal coil being nearer one face than the other. Using this data, the bar size is arrived at by an iterative procedure that proceeds with a guess of the bar diameter. Whilst this algorithm could be encoded, the motion requirements for an automation system would lead to prolonged cycle times. For this reason, the possibility of a single pass method was investigated, because this would substantially simplify the automatic scanning task.

A series of detailed profiles were obtained for groups of isolated bars of different diameters and offsets from the face of the probe. From this, it was apparent that the mid-height width of the profile tended to increase with bar size and depth of cover. In response to this observation, a theory has been worked out for a single pass method. While not feasible with human handling, this takes into account the considerations of transverse bars, adjacent parallel bars and overlapping parallel bars. A large number of trials were carried out to test the theory. For typical reinforced concrete designs found in full-scale structures, the method gives accuracy better than that required for normal site conditions (BS 1881, 1998).

4.1.2 Defect detection using impact echo

Figure 5 illustrates the operating principle of the impact echo (IE) method (Sack and Olson, 1995). While commercially available, it is not yet established in the industry. It comprises an impactor and accelerometer receiver, within a hand-held unit weighing 1.3kg. Although not essential, water can be used to enhance coupling of the device. The
unit is held against the concrete surface and the impactor activated by a finger trigger mechanism. It is linked to a PC-based spectrum analyser, which facilitates investigation of the frequency spectrum response and data storage. The depth of a defect interface, which reflects the stress wave, is determined approximately using the relationship: Depth = (speed of sound)/(2 × frequency). Voids, delamination, low density concrete and other important defects can be detected with varying degrees of success. Regions with low strength and density show up as having abnormal thickness.

For planar delamination in the vicinity of reinforcing bars (a common occurrence due to rust expansion), detection accuracy is of the order of ± 5mm for a defect depth of 60mm. However, accuracy is affected directly by the calibration for the velocity of sound. Excluding interpretation time, which depends significantly on training and experience, productivity is up to 30–60 sample points per hour in the manual application. The main time factor is signal interpretation, indicating the need for information technology.

To investigate this point, a back propagation, artificial neural network (ANN) model was trained and applied to detection of manufactured defects within large concrete slabs. Fast Fourier transformation (FFT) was used to convert the signal from the time domain to the frequency domain. Thus the input nodes are the amplitudes at 512 frequency bands over the range 0-20kHz. One hidden layer is used with the output node set as the frequency corresponding to the defect. On account of the large number of nodes, several thousand training sets were needed. Table I shows the results, which are generally reliable. In the table, IE refers to the manual interpretation of the frequency spectrum. While further verification is necessary, particularly including training data for a variety of defects, this approach would be very positive to automation of the IE technique. Substantially higher productivity could reasonably be expected, possibly as high as 1,000 sampling points per hour,
depending mostly on the robot’s point-to-point performance.

An experimental, wheel based version of the probe is available, which has a solenoid driven impactor giving rates of 2,000-3,000 points per hour. Provided that a suitable carriage can be provided to cater for possible irregularities on the concrete surface, the unit would be suitable for use with a remote handling system. Point-to-point sampling by robotic handling would be a substantially slower alternative.

4.1.3 In situ strength assessment by rebound hammer

Figure 6 illustrates the hand-held rebound hammer (ISO, 1994) employed in the study. As with the metal detector, this provides both visual and analogue output. Use of this device is well established in the concrete inspection industry. To operate the hammer, it is loaded by pushing it steadily against the concrete surface until the load spring is released. This gives a rebound number, which can be related to the shallow strength of the concrete. The rationale for this is that the apparent surface stiffness relates to the elastic modulus, which is found to correlate with strength. Where appropriate, corrections need to be made for the inclination of the impactor. With manual operation, productivity is typically five or more readings/minute.

In trials, the erosion rate was found to relate to the cube strength of the surface concrete. For this reason, spatial mapping of estimated concrete strength is of considerable interest in predicting the hydro-erosion process. In a comparative study for the rebound hammer, pulse velocity (ultrasound) and their combined use, correlation coefficients (detected strength vs cube strength) were reported as 0.93, 0.84 and 0.97 respectively for concrete in the 18-42N/mm² strength range (Goncalves, 1995). However, the general view is that the accuracy of prediction, with correct calibration, is in the 85-90 per cent range.

The weight of the rebound hammer examined is 0.6kg and the force required to compress the spring to firing point is about 120N, with a tip displacement of 15mm. It is necessary to maintain good contact at all times with the device barrel perpendicular to the surface. Results are averaged from multiple readings at close proximity. For a powered handling system the reactive shock load needs to be taken into account, although, in view of the probable machine/tool mass ratio (> 400) of a full-scale industrial system, it may not be a significant issue.

Over a planar surface, XYZ Cartesian motion is the minimum manipulation requirement. Without recording results, the fastest rate of reloading was found to be about 20/minute. With digital recording, a robotic

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<th>Case</th>
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Figure 6 Digital rebound hammer
The sensor data can either be dependent or independent of others. When they are dependent, their association is known as serial distribution. This means that the datum of one sensor just makes sense when the datum from the previous one has been obtained, in other words, they complement each other. In an independent situation each datum makes sense individually. In our case, we have the possibility of both, though a parallel basis is adopted. It is necessary to be sure that the sensors are providing accurate results, otherwise this will have a detrimental effect on the final decision. Using multiple readings at each data point (8-10), statistical analysis is applied to determine this. The detection probability criteria are tested, where, as the name implies, the sensor’s probability of detection is checked. Depending on this probability, they have a higher or a lower certainty weight, \( \eta \).

Typical values for sensor performance are:
- Rebound-hammer (correlated): 93 per cent \( (\eta = 0.93) \).
- Presence of staining: 15 per cent \( (\eta = 0.15) \).
- Reinforcement cover: 85 per cent \( (\eta = 0.85) \).
- Impact echo: 60 per cent \( (\eta = 0.6) \).

The fusion model algorithm has been implemented in Visual Basic, though not with a high-level user interface. A repair index, contour map result is shown in Figure 7. These contours change, sometimes significantly, with alteration of \( \eta \) value, i.e. by downgrading or upgrading the contribution a particular sensor(s) makes to the final condition index. Although outside the scope of the study, a commercial software implementation of the model would usefully have the following attributes:
- sensor data capture (on board A/D);
- processing for sensor statistics;
- online contour maps for sensor data and index;
- multipliers for “what if?” studies on sensor contribution;
- rule base logic for conditioning/linking sensor contributions;
- historic review;
- flexible reporting;
- coordinate-index data for robot task planning.
5. Conclusions

Hydro-erosion is a water jetting method used for cutting out defective material in concrete repair work. For safety, productivity and other reasons, the method would benefit considerably from robotic handling of probes and tools.

Whilst a significant level of technical risk remains for exploitation of the findings, clarification has been achieved. The use of non-destructive testing data in predicting the hydro-erosion erosion process is confirmed as a worthwhile area for further investigation. Prior knowledge of the content of bars in terms of layout, cover depth and diameter can be exploited in planning and executing the hydro-erosion task. A theory has been worked out for the detection of bars that enables all reinforcement information to be estimated from a single pass over the surface of the reinforced component. Experiments conducted in robotic manipulation of the probe indicate that greater accuracy and productivity can be expected than with manual handling. Whilst not yet adopted by the industry, the IE method seems capable of detecting different concrete defects. Automatic detection of buried planar defects is feasible by neural network training and analysis of IE data. The nature of the probe and method of operation lend this method to automatic handling, with a high density of data points rapidly collected and interpreted.

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