Automation and Robotics in Construction XI
D.A. Chamberlain (Editor)
1994 Elsevier Science B.V.

Productivity Analysis of Bridge Inspection Robots

Anna McCrea

Senior Lecturer, School of Construction, Economics and Management, South Bank University, London; Researcher at the Robotics Unit, City University, London.

ABSTRACT

Major objectives in the automation of bridge inspection are the reduction of manpower costs, increase productivity and elimination of risk to human life. This paper relates a productivity study of two different robot configurations for different types of load, bridge geometry, probe specifications,task definition and motors powering (acceleration and velocity). The setting up time, including commissioning and decommissioning is considered in this. The results were then compared with the current operational and servicing costs, as the commercial success depends on these.

1. INTRODUCTION

The paper presents progress in the research on a bridge inspection robot and builds on a previous paper presented during the 10th ISARC [1].
A library of benchmarks has been further developed which covers, among other things, geometrical description of bridge zones and available access to them. As the main task of any inspection robot is to carry a variety of probes, different NDT (non-destructive testing) packages were analyzed and three common and necessary tests in bridge inspection picked for further analysis. This paper covers two aspeects of the effectiveness of robots in inspection, the influence of robot configuration and the relative performance of robots to the current manual activity.

2.TWO ROBOTS FOR NDT TASKS

The NDT and the corresponding probes as tasks for automation were analyzed. The suitability of each probe for use on the robot was assessed taking into account various factors, such as size, weight, simplicity of handling, number of separate operations needed to complete a test and the importance of the test.
The final choice of NDT tasks for further analysis included resistivity measurement, rebar detection and cover, and half-cell potential. Resistivity and surface potential are used as indicators of rebar corrosion. The detection of the reinforcement and its concrete cover depth are important as they tend to indicate vulnerability.

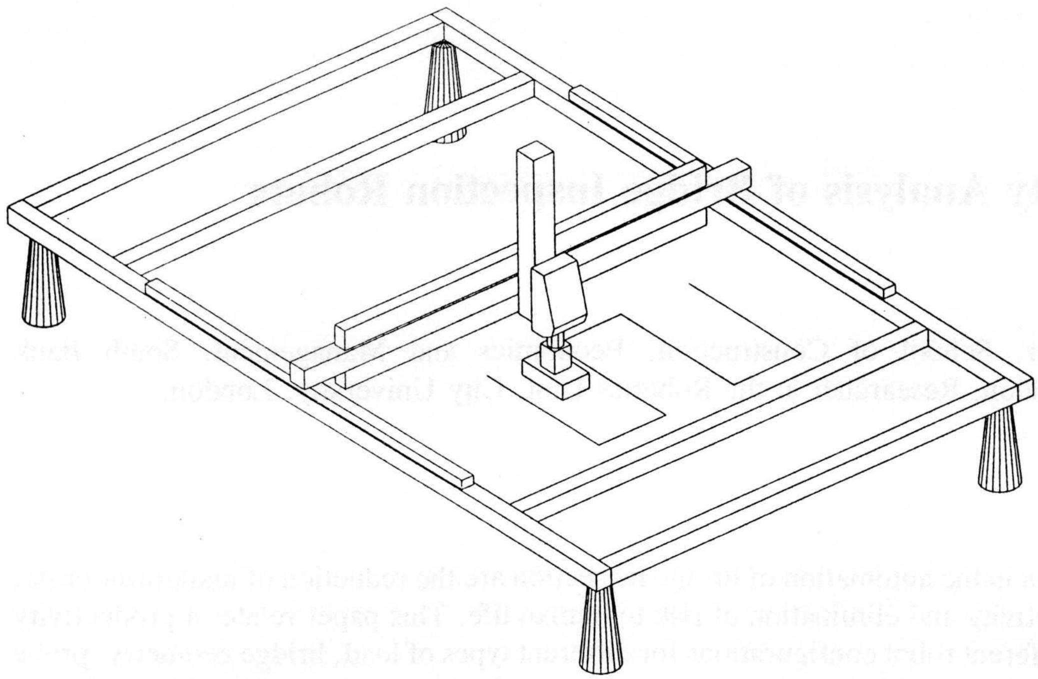

Fig.2. The Five DOF Robot

Data	Robot 1	Robot 2
DOF	5	6
Type	Gantry	Puma
Max. Velocity	500mm/s	500mm/s
Max. Acceleration	250mm/s2	250mm/s2
Weight	40kgs	50kgs
End Manipulators	Pitch, Roll	Pitch, Roll, Yaw

Table 1. Comparison of Two Robots.

3.PRODUCTIVITY EXPERIMENTS

The provisional velocity and acceleration requirements were set after considering the general motor payloads and realistic powering of them in view of cost and weight. The results of the productivity study in terms of completion times are plotted as a series of graphs to show:

(i) the relative performance of the two robots on identical tasks (Fig.3), task 1 represents the area of 250mm*500mm and the contact is made along three paralell, 250mm long lines, while task 2 is the area of 1000mm*500mm with probe lowered to the surface at grid points (250mm*500mm);

These tests were chosen because of their extensive use and different types of coverage required for the area under inspection. Resistivity measurements are made on a grid of points (usually 500mm*500mm), half-cell needs continuous line contact with the surface and covermeter readings have to apply to the whole surface. By means of simulation, using the GRASP software, relevant sequences of robot positions (tracks) were developed. Tracks were applied to two robots. Since it is necessary to keep most NDT probes normal to the surface, at least five degrees of freedom were needed for curved paths. The first robot has six DOF configuration (see Fig.1.) and the second five DOF (see Fig.2.).

The 5-DOF configuration is at present under construction at the City University, London. The limits imposed by geometry and restrictions of movement of joints allow only for inspection of the area within the geometry of the frame. Further, by adding a mobile system, this configuration aims at the effective coverage of large but straightforward areas, such as piers and underside of the flat bridge decks.

Initial work on the 6-DOF robot was previously reported. Here advantage was taken of variable geometry and link lengths to allow the coverage of different types of benchmarks: inverted corners, recesses between the prestressed beams at the underside of the decks and diaphragms to be investigated.

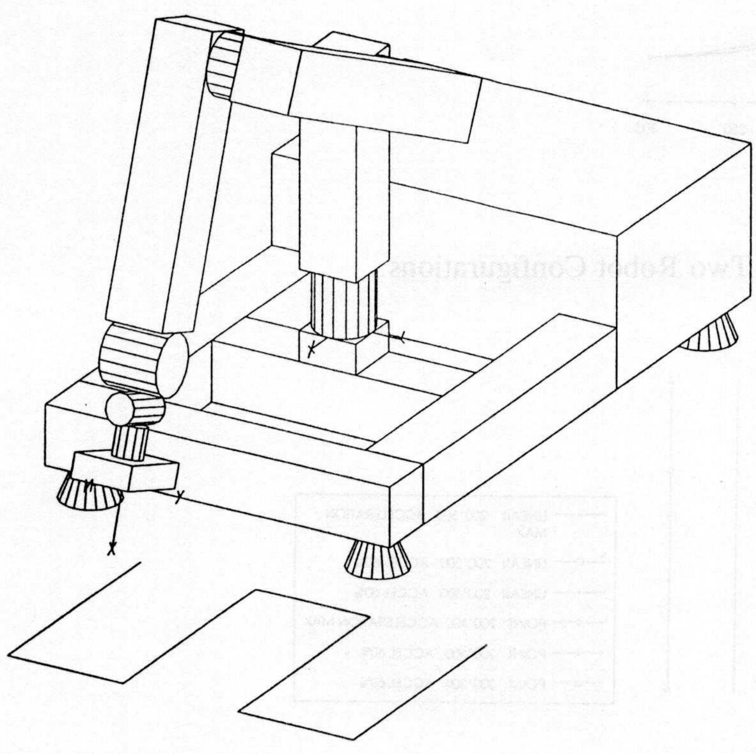

Fig.1. The Six DOF Robot.

(ii) the effects of the maximum velocity and acceleration value (indicates motor power requirement) (Fig.4);
(iii) the effect of the coverage and path requirement for different tasks (Fig.5), for position and type of the curved track see Figs.1 & 2;
(iv) the relative demands due to varied geometry (Fig.6).

On consideration of these results, it is apparent that several restricting factors need to be considered, as they limit the capability for performing wide range of tasks with high productivity.

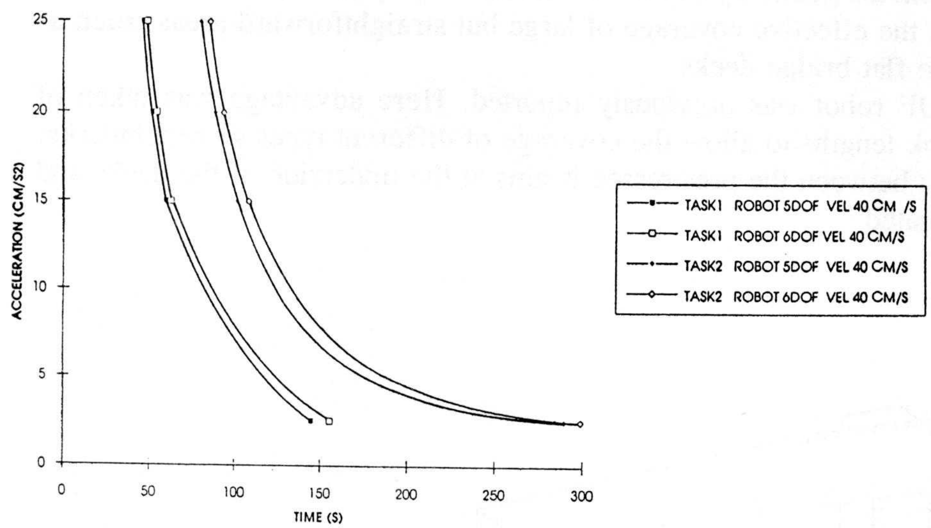

Fig.3. Task Completion Times for Two Robot Configurations.

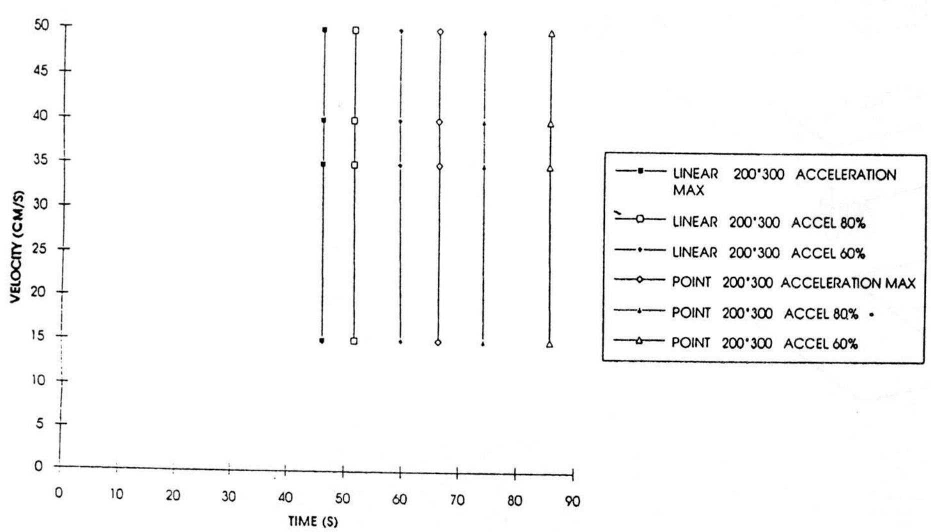

Fig.4. Completion Time as Function of Velocity.

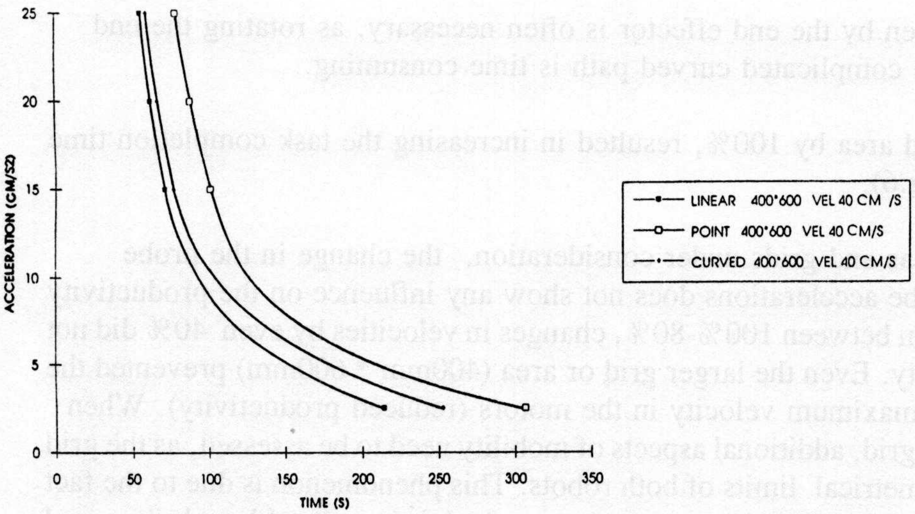

Fig.5. Task Completion Times for Three NDT Tasks.

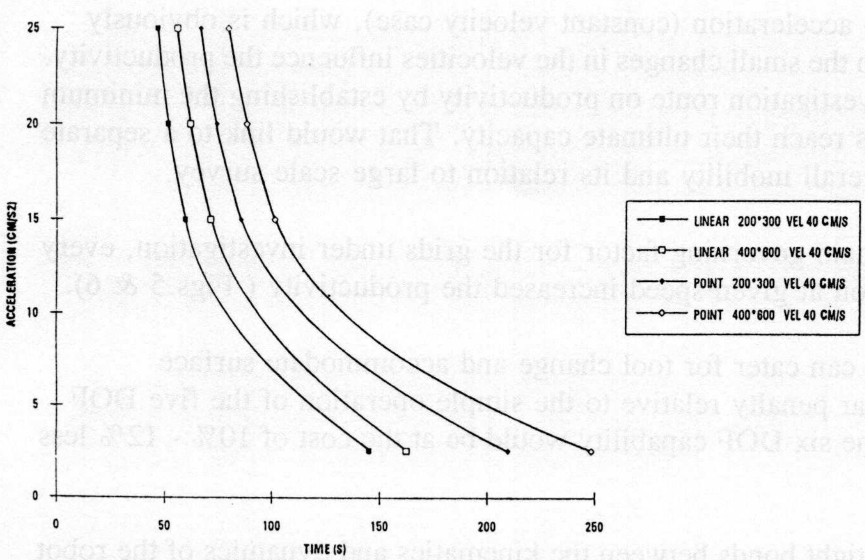

Fig.6. Task Completion Times for Two Benchmarks.

The main experimental observations can be summarized as follows:

i) The most productive area coverage was when the contact with the surface was along the straight, parallel lines at constant spacing. The probe needed to be lifted only to move to an adjacent line. The point contact coverage over the same area reduced the productivity by 42%-45% due to the extra time required to lift and lower the probe to the surface for each reading. Covering the area along constant curved paths took longer by 36%-38% due to the necessity to rotate the probe at each corner of the path (Fig.5).

Control of the path taken by the end effector is often necessary, as rotating the end effectors to follow the complicated curved path is time consuming.

ii) Increasing the inspected area by 100%, resulted in increasing the task completion time only by 18%-20% (Fig.6).

iii) For the sizes of the areas and grids under consideration, the change in the probe velocities for given probe accelerations does not show any influence on the productivity (Fig.4). With acceleration between 100%-80%, changes in velocities by even 40% did not influence the productivity. Even the larger grid or area (400mm * 600mm) prevented the robot from developing maximum velocity in the motors (reduced productivity). When investigating the bigger grid, additional aspects of mobility need to be assessed, as the grid extends outside the geometrical limits of both robots. This phenomenon is due to the fact that the maximum achievable velocities are never reached for small (although the word 'small' has relative meaning only) grids, therefore one can conclude that the size of the grid has a bearing on productivity, providing the grid is sufficiently large.

iv) Only when assuming zero acceleration (constant velocity case), which is obviously totally unrealistic, do even the small changes in the velocities influence the productivity. This could suggest the investigation route on productivity by establishing the minimum area for which the motors reach their ultimate capacity. That would link to a separate study on the means of overall mobility and its relation to large scale survey.

v) As acceleration was the main governing factor for the grids under investigation, every increase of the acceleration at given speed increased the productivity (Figs.5 & 6).

vi) Whilst the six DOF robot can cater for tool change and accommodate surface undulations, there is a clear penalty relative to the simple operation of the five DOF robot. Full utilisation of the six DOF capability would be at the cost of 10% - 12% less in productivity (Fig.3).

Some of the results prove the tight bonds between the kinematics and dynamics of the robot (i and v). Once the trajectory is determined, the remaining problem is to program the joint actuators to cause the manipulator to follow the planned trajectory. However to ensure the productivity it is necessary to combat possible motion induced vibration in the lightweight robot architecture.
In many applications the robot does not have to be driven at high speed which simplifies the dynamic model, however the improved dynamic performance of manipulators using realistic dynamic models is still to be achieved if the productivity can further raise [2].

4. COLLISION AND MOTION TRAJECTORIES

Collision checking imposes restrictions on the geometry of the robot for the given access requirements for the probes with potential incompatibility between the geometry of some of the inspected zones.

In order to prevent collision between the probe and the target geometry in the working space of the robot, collision conditions are classified with the various factors relating together the choice of the path of a probe, location of obstacles (diaphragms to underside of the deck, piers, etc.), the configuration of the joints of the robot, geometry of the robot determining desired values of the machine coordinates and means of access.
If the motion trajectory cannot be applied without collision, the path has to be modified by looking for alternative trajectory patterns. The practical alternative is to look for different types of probes for the same type of NDT which also means looking for different area coverage, possible change of grid layout and sizes, which would require repeating the initial productivity analysis taking into account change in weight and size of the probe.
A more theoretical approach is to implement the path control - PTP - Point to Point (controlling the speed and acceleration of TCP) against CP - Controlled Path (speed of each joint can be controlled independently) represented in so-called guarded motion. The path of the end effector can be further constrained by the addition of via-points intermediate to the initial and final configurations [3]. For high collision risk activity, such as found in NDT tasks, continuous path control is more or less essential for physical implementation.

5. AN ECONOMIC ESTIMATE

To economically appraise the use of automation in bridge inspection, the cost effectiveness, productivity and effect on quality need to be assessed. From the productivity study, the greatest increase can be observed on relatively large surfaces. This fact can be advantageous on large, high, multi-span bridges. From a study on the criteria governing the application of automation [4], factors such as dangerous environment and special skills are high on the list for priority in automation. Due to difficult, dangerous and expensive access involving abseiling, complex suspended platforms, etc., automated bridge inspection is an economically sensible activity. The cost justification has to be done for two main aspects: access equipment and manpower.

The sample of the access cost Nov. 1993 indicates:

- power operated suspended platforms	£750	-	£900 pw
- large scaffolds	£1200	-	£1400 pw
- long mobile lifting platforms	£500	-	£700 pw
- cradle on guy ropes	£200	-	£300 pw
- abseiling	£200	-	£300 pw

Sample cost of NDT manpower involvement Oct.1993:

- rate per hour - £15 - £25;
- covermeter survey (no access problems), area 50 m2 - -8 days and one person;
- visual inspection (med. amount of cracks and defects) -20 m2 - 2hrs;
- medium overbridge over minor road (visual inspection, half- cell potential mapping, cover check, depth of carbonation with drilling and the report) - £3000 - £5000;
- half-cell potential mapping - 4 readings per minute on 500mm*500mm grid;
- resistivity - 25 m2, one man in 3 days;
- report preparation - 3 hours per sheet;

5.1 Comparative Study

A comparative assessment of productivity and cost of manual versus automated inspection was carried out for the middle span and two inner faces of piers of the Medway Bridge, near Maidstone, Kent. The results have been obtained for the 5 DOF robot and manual survey. Assumptions for the work area are as folloes:

- top deck area - 5256 m2
- underside of the prestressed beam - 3790 m2
- two inner faces of piers - 335 m2.

Assume 5% sample to allow for selective choice of inspected areas based on visual assessment.

Manual Inspection

time for 3 probes for the deck	- 605 hrs
as above for the u/s of the deck + fatigue	- 605 hrs
time for 3 probes for piers + platform movement	- 40 hrs+ 50hrs
total time	- 1300 hrs
labour cost	-£ 26 000.00
cost of hiring the access platform	-£ 13 000.00
total cost	-£ 39 000.00

Assume 25% sample to allow for only occasional relocation to other inspected area.

Automated Inspection (5 DOF Robot)	
time for 3 probes for the deck with relocation (0.5hr)	- 8hrs+ 45hrs
as above for the u/s of the deck	- 6hrs+ 35hrs
time for 3 probes for piers + platform movement	- 30hrs+ 25hrs
total time	-150hrs
cost of hiring the robot (£2000.00 pw)	-£ 8000.00
cost of technical staff	-£ 1000.00
cost of hiring the access platform	-£ 9000.00
total cost	-£ 18 000.00

6. CONCLUSIONS

The analysis of the productivity study directs the research towards more economical robot configuration and geometry and indicates the choice of the NDT testing techniques. The examination of the influence of the velocity and acceleration leads to the realistic powering of motors and estimating the true weight.

The productivity check combined with the simple cost effectiveness exercise points the direction for further research in bridge inspection automation towards large, high and difficult access structures, providing a reliable and mobile access system is designed. The outcome of the approximate cost analysis shows that the productivity could be as much as 200% higher and the cost halved, if automation is applied to bridge inspection.

7. REFERENCES

1. McCrea A., Chamberlain D., 'Towards the Development of a Bridge Inspecting Automated Device' - Proc. 10th ISARC, Houston, USA, May 1993.
2. Filaretov V., Mimohod P., 'System of Automated Design of Control Mechanism for Manipulators Having High Dynamic Accuracy' - Proc. 9th ISARC, Tokyo, Japan, June 1992.
3. Spong M.W., Vidyasagar M., 'Robot Dynamics and Control' - J.Wiley & Sons.,1989.
4. Arditi D., Sundareswaren S., Gutierrez A., 'The Future of Automation and Robotics in Construction Activities' - Proc. 7th ISARC, Bristol, U.K., June 1990.