THE SELF-TUNING OF ROBOT PROGRAM PARAMETERS FOR MANIPULATING FLEXIBLE PARTS.

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Abstract

This paper introduces the problem of vibrations in manipulating flexible beam and sheet materials in the construction industry. Analysis and experimental investigations show that translation and rotation of components can set up vibrations that are unacceptable in terms of damage to the parts or unnecessarily long settling times at the end of each motion. The paper describes a motion parameter search method that allows the robot to self tune its motion to satisfy task requirements, such as minimum transportation time without damage to flexible and vulnerable parts. In this approach the robot is programmed to learn about the parts it handles by making small changes in the motion parameters. The knowledge of the part and the task is gathered over a number of cycles eventually leading to selection of a "best known solution". It is suggested that this paper will be of interest to those involved in automation and robotics in site processes, including structural steel fabrication erection. It should also interest those seeking to apply robotics for building products and component manufacture.

1. Introduction

In the construction industry the manipulation of flexible parts abounds. The materials that fall into this category include pipe, rod, and sections in steel and non-ferrous metals and non-metals. Construction also involves the handling of beams and sheets made from wood or wood products and other sheet materials such as plasterboard and composite boards. In factory automation problems that arise from the use of flexible materials can often be solved by the use of specially designed tools and grippers which give the material adequate support, overcoming vibration and undesirable distortion during transportation and manipulation [Refs. 1, 2, 3]. This approach is reasonable provided that large specialist grippers are acceptable. However, in the construction industry the handling systems have to be able to deal with a wide range of different components and parts can be of such a large size that prohibitively large specialist tools would be required. In this instance scaling up from factory automation is not viable and so a more subtle means of dealing with part vibration must be found.

Although this work originally stemmed from an interest in the robotic assembly of flexible aerospace components [Refs. 4, 5] it was quickly realised that the approach was also applicable to many other areas of industry including construction. At the present time most of the handling in construction is manual or under direct manual control. Only in certain areas of building products manufacture has handling automation found a place and even to that extent the automation is dedicated and inflexible. In both manually controlled and automatic handling the method for dealing with part vibration is universally to use low speeds and make ample allowance for vibrations to settle at the end of each motion. Although experience and the experimental work described here will confirm this crude and expensive strategy as "probably" safe, in the eventual application of automation, cycle time will become more critical and it will be necessary to derive a more aggressive attitude to optimising the handling process.

Although the programming of a robot or setting of an automatic handling system may not be time consuming, the tuning of that program to minimise load on the parts being handled and minimise the handling time, could itself be a painstaking, laborious and time consuming task. In the approach described here, the robot is programmed to search the motion parameter space (acceleration, velocity, deceleration) seeking the combination of these parameters which best suits the part and the task. This adaptive learning approach does not require a mathematical model of the vibration of the machinery or the part and can deal with highly complex multi-modal and non-linear vibrations provided the component parts of the system behave and interact consistently.

The problem of tuning a robot program has been clearly identified and expressed in work by Weiss et al., [Ref. 6]. In the self-tuning approach described and applied by Weiss and applied in the present work, the motion primitives have adjustable bounded value parameters which are manipulated to seek optimal or improved performance. An earlier paper by the authors [Ref. 4] applied the technique to the transportation of a flexible cantilever beam. Other researchers [Ref. 7] have analysed the angular acceleration of a cantilever beam and proposed the mathematical model to describe the beams vibration. This present work extends the self-tuning method to the rotation of beams as well as dealing with the elevation of sheet and tube. Fig. 1 illustrates these various arrangements.

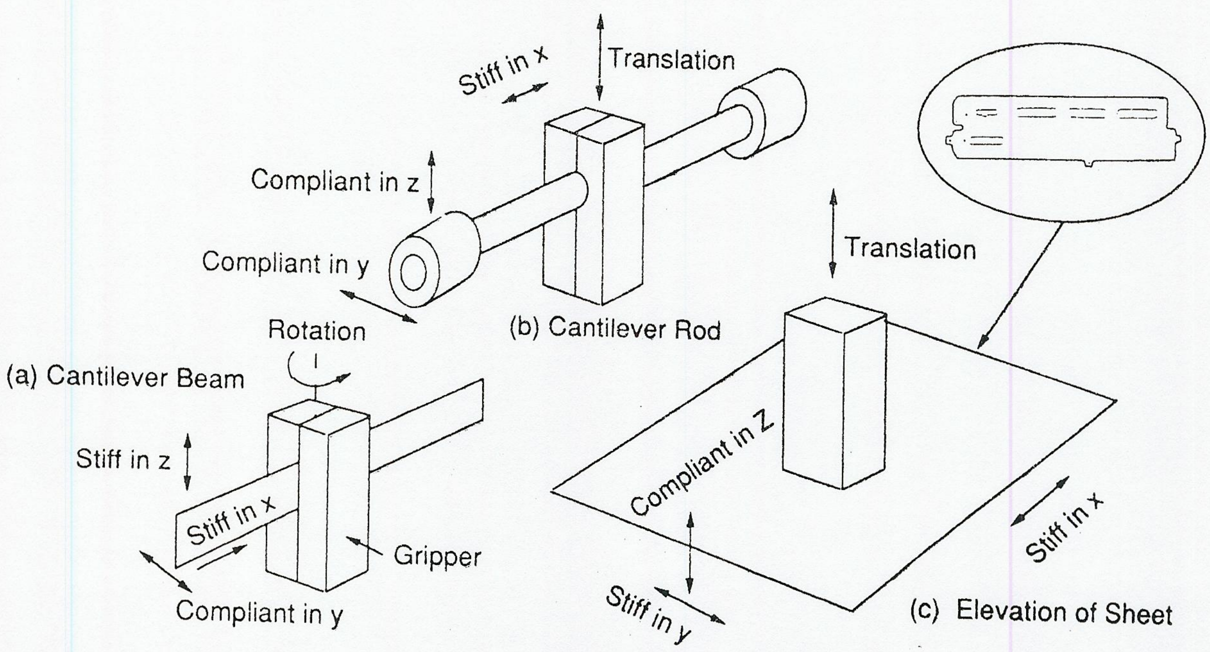

Fig. 1. Experimental handling arrangement of parts.

2. Theory

Although in this approach it is not necessary to mathematically model the parts or their vibrations a simple model of the rotation of a cantilever beam, see Fig. 1(a), was useful to illustrate the principle of the technique. Firstly, the system can be idealised to an under-damped linear single degree of freedom, second order system [Ref. 8], which is not significantly different from the case dealt with by the authors in an earlier paper [Ref. 4]. As with the previous work, assuming zero initial conditions and taking the Laplace transform of the equation of motion, a transfer function of the form

$$G(s) = \frac{Y(s)}{X(s)} = \frac{2\alpha s + \omega_n^2}{s^2 + 2\alpha s + \omega_n^2} \qquad (1)$$

was obtained. A control software package known as PC-MATLAB[1] was used to simulate the system using values of damping constant (α) and natural frequency (ω_n) which were obtained experimentally. The traces shown in Figs. 2(a) and (b) show the theoretically predicted response in terms of vibration of the beam when subjected to a rotation of 90 degrees using different acceleration profiles. Note that in trace (a) the displacement of the part is large at the instant the rotation of the gripper ceases. This results in the prolonged residual vibration of the part. As a consequence, such a situation may require a long settling time before the part could be moved to the next position. In trace (b), a slightly reduced acceleration and deceleration setting results, in the end of the gripper motion coinciding with a near to node position of the beam. In this situation the part has only a small amplitude of residual vibration and may be moved on with little or no settling time.

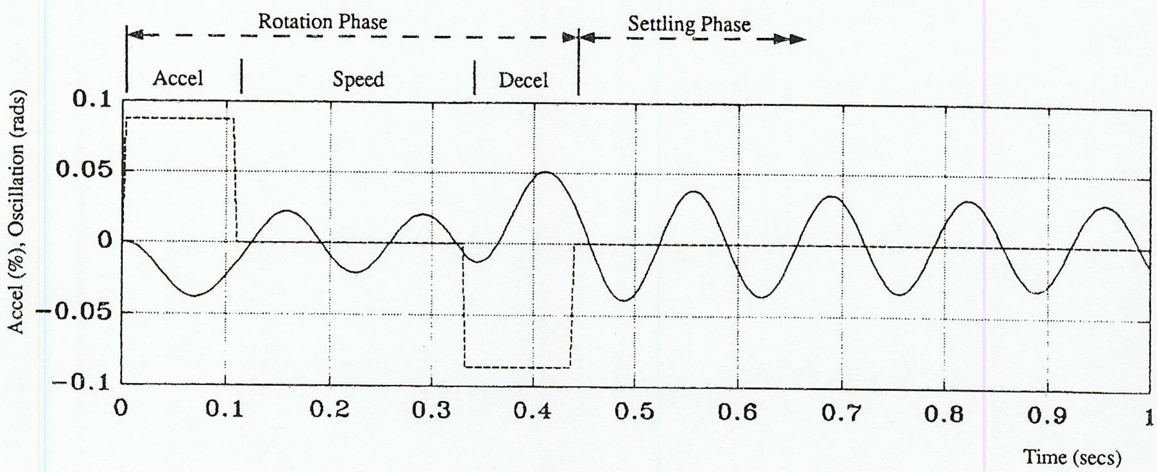

Fig. 2(a). Modelled acceleration profile and oscillation of part for unfavourable condition.
(Acceleration factor = 1.0, Speed factor = 0.70, Deceleration factor = 1.0)

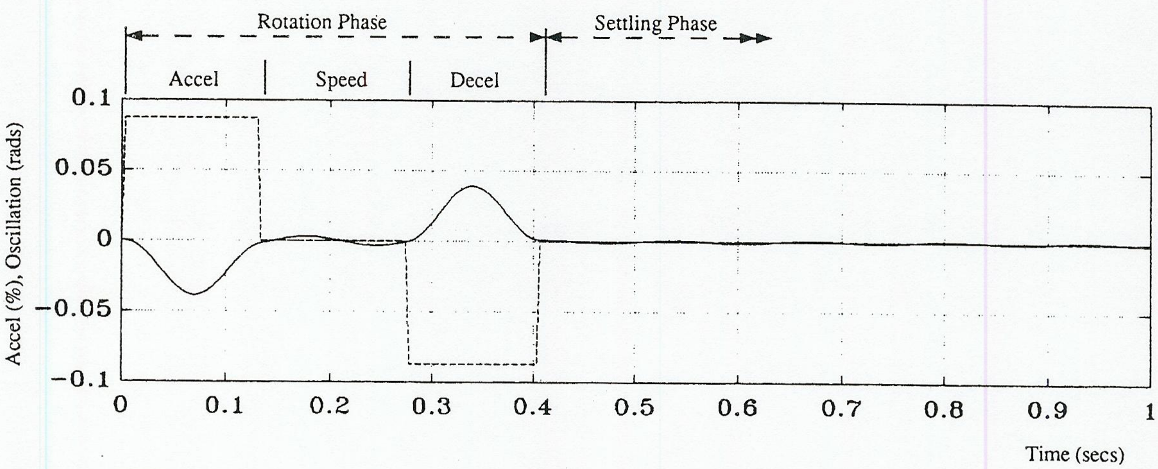

Fig. 2(b). Modelled acceleration profile and oscillation of part for favourable condition.
(Acceleration factor = 1.0, Speed factor = 0.84, Deceleration factor = 1.0)

This theory section is concluded by stating that a technique for searching through the parameter space to find combinations of acceleration, velocity, and deceleration which result in reduced load on the workpiece and reduced settling time should be independent of the modes of vibration of the parts. As a consequence the approach should be applicable for the more complex cases described in Figs. 1(b) and (c).

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[1] The Mathworks Inc. ®

3. Experimental Set-up

The mechanical hardware of the system consists of an IBM 7565 hydraulically powered gantry robot with a rectangular box-frame supporting a single manipulator arm with three linear and three rotational degrees of freedom and a two-finger gripper with parallel acting jaws. The system controller has a digital I/O interface and a RS-232 serial line which has been used to communicate with an IBM PS/2 50Z micro computer which coordinates the self-tuning strategies for each robotic task. The robot is equipped with sensors mounted on the manipulator arm and end-effector. An accelerometer provides the acceleration forces experienced by the arm during motion and strain gauges mounted on the parts produce vibration signatures. The strain gauges are arranged in a half wheatstone bridge configuration. The PS/2 is fitted with a 12-bit high speed analogue and digital I/O data acquisition board that provides eight differential analogue input channels, two analogue output channels and sixteen digital lines which may be configured for input or output or both.

The programming/control environment of the IBM 7565 is AML (A Manufacturing Language), an interactive manipulator level programming language in which only the positions of the end effector, relative to some reference point, need to be specified. The majority of programming done on the PS/2 is written in Microsoft C and these programs perform all the data acquisition functions, data analysis, search strategies for motion parameters and handle all the asynchronous communications over the serial line. Simple low level device drivers have been written for this purpose. More specifically, the commands to control the data acquisition board form part of a suite of functions provided in a package known as PS/LAB[2]. It is supplied by the manufacturers of the A/D board and runs under DOS.

4. Method

The self-tuning experiments described in this paper began as an investigation into the effect of the motion parameters when performing a single axis rotation of the manipulator when gripping a cantilever beam. The beam consisted of a length of 1.6 mm gauge aluminium with dimensions 52 mm deep by 407 mm long. The beam carried a concentrated mass of 22.8 grams at the free end to reduce the natural frequency of vibration and maintain a primary mode of flexing. It was gripped in the parallel jaws with a gripping strength of 1200 grams. The three robot motion parameters: angular acceleration, angular speed and angular deceleration were expressed in the AML software as percentages of the maximums attainable for the robot (without a gripper load) and are 2500 deg.s^{-2}, 389 deg.s^{-1} and -2500 deg.s^{-2} respectively.

Using the automatic data collection facility an automated experiment was developed and run which performed the following functions; initialisation of robot and PS/2 communications, motion parameter adjustments, robot movement commands, data collection and analysis. A sequential search of the parameter space was conducted beginning with each motion factor set to its maximum of 1.0 and then decreasing each parameter by a fixed resolution of ten percent in the order angular deceleration, angular speed and angular acceleration. This generated a total of 1000 runs taking approximately two hours to perform. For each experimental run, i, there were three primary factors of sensory information extracted from each parametrized transport primitive. These included the total transport time for the robot motion, t_i, and the peak oscillation amplitudes occurring during rotation and during the settling or free oscillation phases, $(o_r)_i$ and $(o_s)_i$. The maximum transport time, t_{max}, and maximum oscillation amplitudes for each phase, $(o_r)_{max}$ and $(o_s)_{max}$, were determined to allow the normalization of the results. It was also desirable to decide values for the terms, $(o_r)_{thr}$ and $(o_s)_{thr}$, which represent maximum limiting threshold oscillation amplitudes derived from the task requirements. The results were saved to disk and then post

[2] Data Translation Ltd. ®

processed through a cost function algorithm [Ref. 6] from which optimum operating parameters were found. For this experimental run the cost function takes the form,

$$J_i = \frac{k_1}{k_T}\left[\frac{t_i}{t_{max}}\right] + \frac{k_2}{k_T}\left[\frac{(o_r)_i - (o_r)_{thr}}{(o_r)_{max} - (o_r)_{thr}}\right]_{rotation} + \frac{k_3}{k_T}\left[\frac{(o_s)_i - (o_s)_{thr}}{(o_s)_{max} - (o_s)_{thr}}\right]_{settle} \qquad (2)$$

$$k_T = k_1 + k_2 + k_3$$

The algorithm used in deriving the data given in the results uses weighting coefficients that are in line with the desired task goals of moving a flexible part in the shortest possible time with minimal overshoot at the end of the trajectory. The reduction of task cycle time is given a high profile ($k_1 = 1.0$) with the same value also given to reducing peak oscillation during the settling phase ($k_3 = 1.0$). Correspondingly, the peak rotation amplitude value is given less attention ($k_2 = 0.1$) in this typical handling case. It should be noted that the form of the results from using this cost function approach would be different for different values of (k_1, k_2, k_3) and in application it would be necessary to match (k_1, k_2, k_3) values with the requirements of the task.

A similar procedure was then followed using a sheet type workpiece. The sheet was 0.9 mm thick flat aluminium measuring approximately 500 mm by 145 mm and was a relatively complex shape having a number of irregular perforations and holes, as indicated in Fig. 1(c). The motion of the sheet investigated was as illustrated and consisted of a 200 mm vertical motion. The method of gripping was a mechanical clamp acting through a hole at the centre of the sheet. In this investigation two sets of strain gauges were used to provide the vibration signals on each side of the clamping position.

A similar procedure was also followed using a cylindrical tube workpiece as illustrated in Fig. 1(b). The workpiece consisted of super high impact PVC tube (B.S. 6099) and was 20 mm outside diameter and 1.8 mm wall thickness. Weights of 675 grams were added at 345 mm centres from the grip. Strain gauges were used to measure the vibrations in the vertical and horizontal plane. In this particular investigation a vertical motion of 10 mm was used.

5. Results and Discussion

The results for the rotation of a cantilever are presented graphically in Fig. 3. Each figure shows the experimental run number according to the order of the search along the horizontal axis, versus the sensed data along the vertical axis. The first graph, Fig. 3(a), is derived from the use of the cost function and shows variation in cost over the full search space of 1000 runs. The data illustrated in this graph was then used to determine the optimum parameter values for minimum cost and Fig. 3(b) shows the results from running those parameter values over a further 500 cycles.

The graph in Fig. 3(a) shows that across the whole parameter space the values of cost vary considerably for quite small changes in parameters. Study of the graph shows more repetitive features, for example, the regular occurrence of high cost associated with low velocities. A less predictable observation is the consistency of the low cost values with local minima occurring across most of the parameter range. The consistency case in Fig. 3(b) shows little stochastical variation over the 500 cycles and no drift.

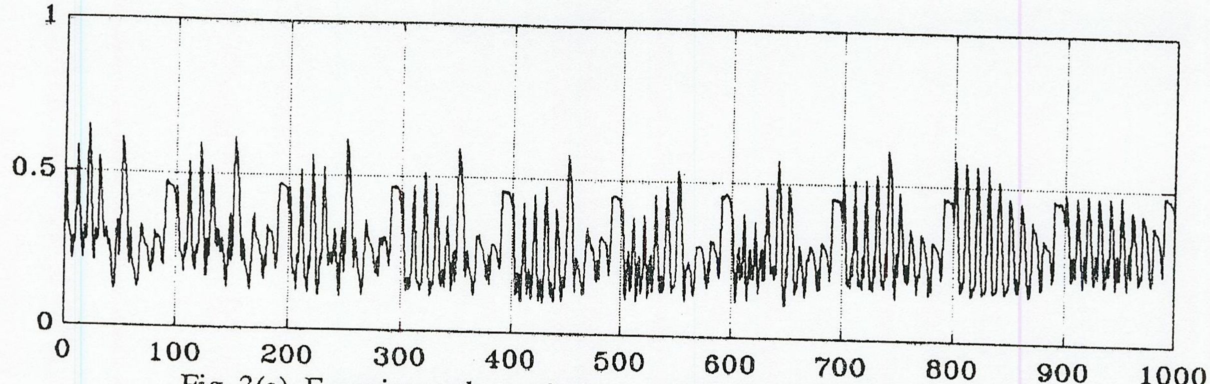

Fig. 3(a). Experimental search vs. cost function for cantilever rotation.

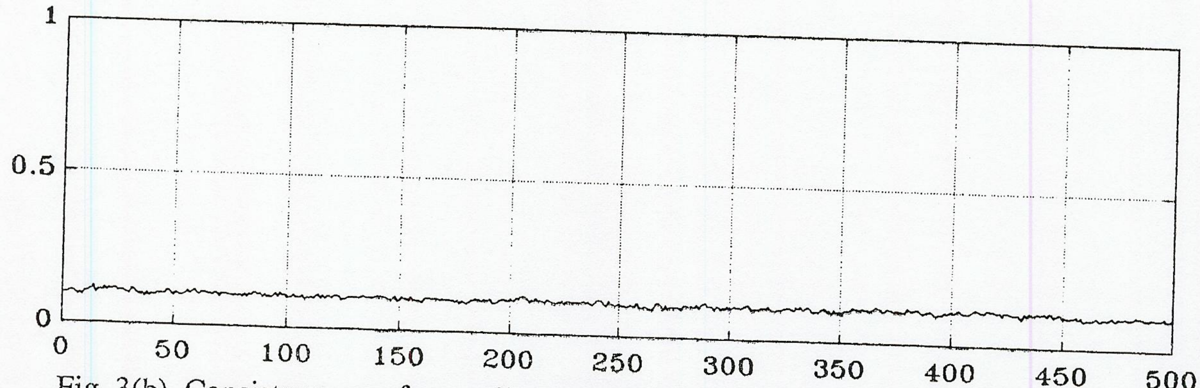

Fig. 3(b). Consistency run for cantilever rotation *(Accel = 0.6, Speed = 0.8, Decel = 0.3).*

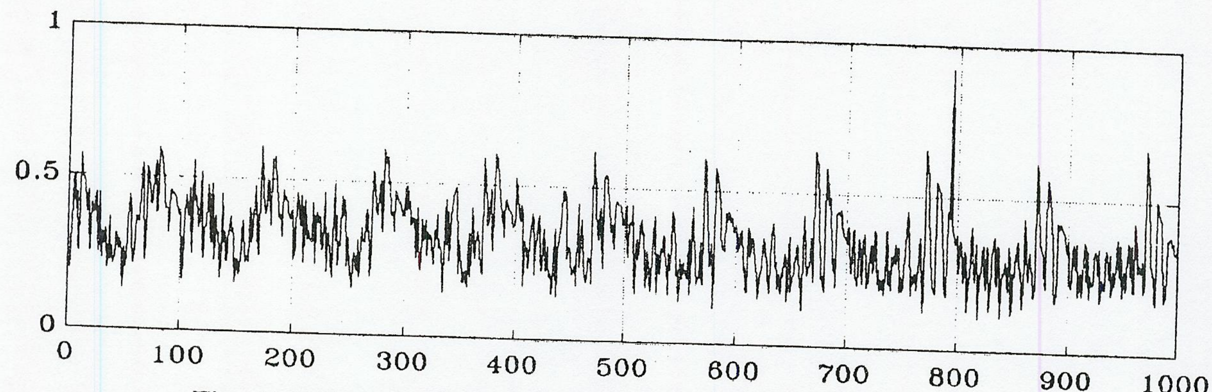

Fig. 4(a). Experimental search vs. cost function for sheet translation.

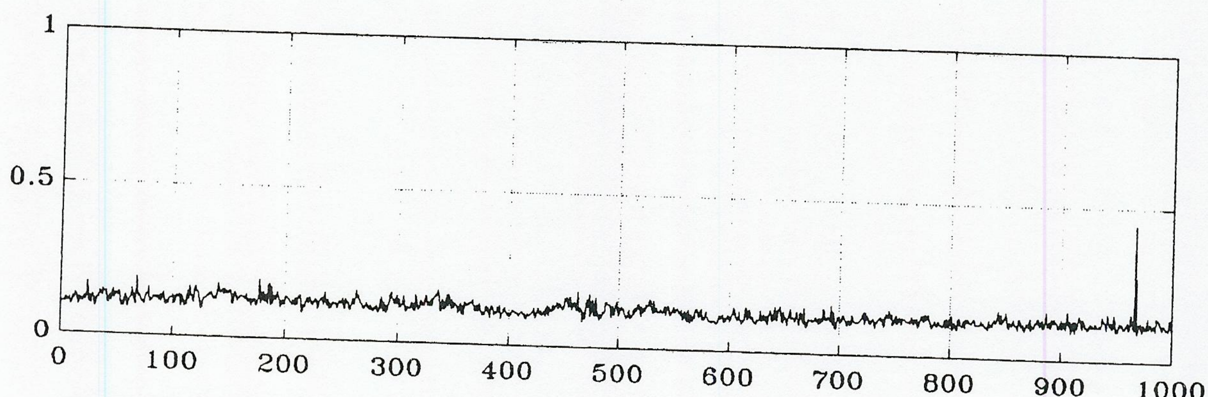

Fig. 4(b). Consistency run for sheet translation *(Accel = 0.2, Speed = 0.9, Decel = 0.2).*

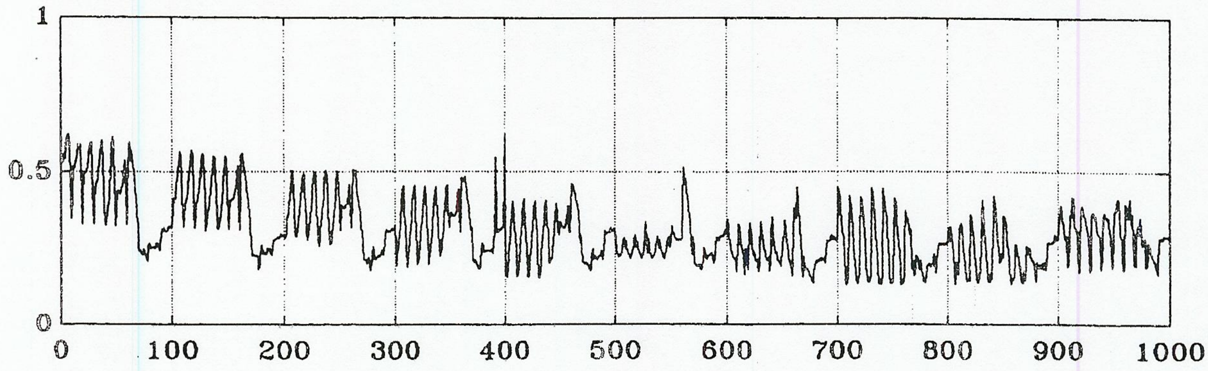

Fig. 5(a). Experimental search vs. cost function for tube translation.

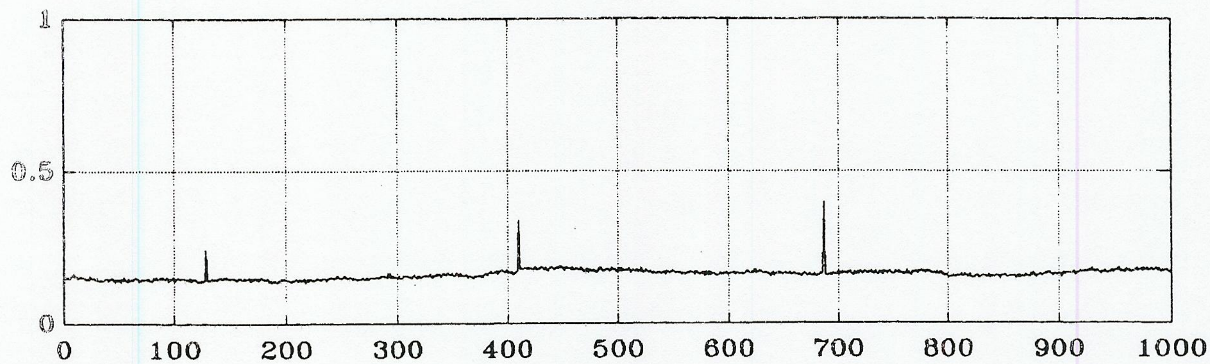

Fig. 5(b). Consistency run for tube translation *(Accel = 0.03, Speed = 0.05, Decel = 0.04)*.

Although the vibration of the sheet workpiece is obviously more complex than the simple cantilever the results for the sheet shown in Figs. 4(a) and (b) are similar in form. Once again the cost graph shows large variations of cost for relatively small changes in the parameters. The selected optimum was found to be consistent when tested over 1000 runs, although the complexity of interaction of multi-modal vibrations lead to greater stochastic variation about the prescribed optimum.

In the case of the elevation of the PVC tube preliminary investigation indicated that large parameter values (high acceleration, velocity and deceleration) produced unacceptable dynamic forces on the robot joints. As a consequence the search window was reduced to motion parameter values of less than 10% and a proportionately finer resolution of parameter adjustment was used. Within this window, the results shown in Figs. 5(a) and (b) indicate the usual rapid variation in cost for small parameter changes but there appears to be a regularity that is not apparent in the other tests. Overall there seems to be a drift towards lower costs for lower acceleration values and for particular acceleration values the cost range seems to be a function of deceleration and independent of velocity. The consistency test at the selected optimum value once again showed small variation in cost and some evidence of long term drift.

6. Conclusion

1. The technique of searching the motion parameter space to find minimum cost was shown to be successful when applied to the rotation of a cantilever and the elevation of rod and sheet workpieces.

2. Once the optimum motion parameters were determined by an exhaustive search the consistency investigations indicated that the parameter values maintain a low cost performance over a large number of cycles. There was only a small amount of statistical variation and little sign of drift in performance.

3. The motion of the sheet and tube was noted to be more complex than that of a simple cantilever and the approach was found to be robust even for these complex multi-modal situations.

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