WEIGHT AND STABILITY ANALYSIS OF THE MULTI PURPOSE INTERIOR ROBOT

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SUMMARY

The article describes some developmental aspects of the Multi Purpose Interior Robot (**MPIR**), a mobile construction robot. The analysis of specific attributes of the robot at the early stage of the conceptual design is discussed. Because numerous designs had to be compared, the analysis' approach is one of simplicity, allowing quick assessments of designs' attributes. The attributes addressed in this article are the robot's weight, stability, and cost.

Keywords: Construction, Automation, Robotics, Graphic Simulation, Cost Analysis.

1 INTRODUCTION

MPIR's working environment is the interior space of a building. This type of environment imposes constraints, some of which are unique to **MPIR**. These problems include weight limitations, stability, and maneuverability. The weight and stability problems are the topics of this article, while the maneuverability problem is discussed in [6,7].

An important concern is **MPIR**'s weight, which should be limited to the building's designed live loads, plus the dead loads of components to be erected later. Any higher value of the robot's weight will cause additional costs for the strengthening of the structure, or for temporary support during construction. One of the parameters in determining the robot's weight is the arm's live load, which is based on the weight of the heaviest component that **MPIR** has to manipulate and/or the tools which are needed to perform the designated tasks.

Industrial robots typically have a high ratio of weight to live loads, which is derived from various requirements introduced by manufacturing, among which is accuracy. Research is being conducted at various universities to reduce this ratio [1,2], but the current state-of-the-art value is too high by an order of magnitude for **MPIR**'s needs. Consequently, the research described herein had to address the problem of the robot's weight, taking into account the live load requirement on the one hand, and the limit of its weight, on the other. Based on those considerations, and the sporadic nature of loads that **MPIR** imposes, its maximal weight was determined as 400 kg.

Because **MPIR**'s assignments exceed its work envelope, **MPIR** has to be mobile, unlike most of its manufacturing counterparts, which are normally attached to the floor. Consequently, **MPIR**'s stability had to be very carefully investigated. The stability problem is amplified due the following:

* The robot's moving base (carriage), which has limited dimensions to enable it to move about its assigned environment, consisting of relatively narrow corridors and openings (doors).
* **MPIR**'s relatively long arm, which enables it to reach distant locations dictated by the nature of its tasks.
* The intensified overturning moments imposed by the dynamic effects due to the motion of the arm.

A typical solution to the stability problem is to increase the weight of the robot's base. This solution is not applicable for **MPIR** because of the weight problem cited above. Another approach is to stabilize the carriage on jacks, which will be spaced far enough apart to provide stability, taking into account the above factors. This solution imposes constraints on the minimal distance between the robot and the walls that it has to work on. It also limits the availability of free space around the robot for the supply of materials.

2 COST ASSESSMENT

The cost assessment of the robot's arm at this early design stage is a demanding task because so many of its parameters are not yet known. Such an assessment is not normally required for the development of industrial robots.

The speed and the simplicity of the estimating process were of prime importance because the research methodology was based on the comparison of a large number of alternatives. A process requiring time-consuming calculations was not practical.

The literature yielded few results. One article (in Russian) did suggest,however, a rapid method for evaluating the cost of industrial robots at the design stage [4]. The article argued that the cost of an industrial robot, C', would be:

$$C' = a_0 * x_1^j * x_2^k * x_3^b \qquad (1)$$

where:

x_1 - the live load in kg;
x_2 - the number of degrees of freedom;
x_3 - the weight of the robot in kg; and
a_0, j, k, b - constants.

The article also gave the correlation between the live load and the robot's weight. Combining the correlation formula with formula number (1) above, and using their constants, resulted in the following for the cost of the robot in Rubles:

$$C' = 151.8 * x_2^{0.758} * x_3^{0.563} \qquad (2)$$

At first glance the method looked very promising because it did offer a quick way to assess the cost of the robot based on the very parameters which were available at the conceptual design stage. Unfortunately, when more closely studied, the method could not be adopted. Two of the main reasons are listed below:

* The article does not specify how the authors reached the formulae, and especially the constants. The impression was that they used a regression method. If this were the case, it would have been very difficult to adopt the method without knowing the sources of the data.
* Based on these formulae, the costs of a series of robots were calculated. A comparison of the results to the actual prices resulted in deviations of hundreds of percent.

Clearly the above method could not be employed.

The comparison of alternatives at the simulation stage related mainly to properties of the robot's arm, in a relatively limited range. All the alternatives had six DOF, a reach of 1.8 - 3.0 m, actuator`s speeds of 100 - 200 degrees per sec, and accelerations of 200 - 400 degrees per sec^2. This allowed a simplified approach, which graded the alternatives according to their relative cost.

In this approach two parameters were used to calculate the alternative's relative cost: the weight of various links, and the type and size of the actuators. Both of these parameters reflected the differences due to various link sizes and different actuator speeds & accelerations. For the purpose of the study, this approach gave better results compared to the ones based on formula (2). It is interesting to note that for a fixed number of DOF, this formula has only one parameter, which is the weight of the robot (or alternatively its live load).

The relative cost, C in $, was consequently calculated as:

$$C = \Sigma FS_i * c + \Sigma c_j \qquad (3)$$

where:

FS_i -the weight of link number i (i= 1,..,number of links).
c -the cost of the link per unit weight.
c_j -the cost of actuator j (j=1,..,number of actuators).

In order to simplify and speed the assessment, manufacturability considerations were not addressed.

The cost of the link per unit weight was calculated based on prices of a number of six-DOF robots. The cost, which was determined in $/kg, was calculated as the average of their differential prices divided by the average of their differential weights. The result, 200 $/kg, was used to calculate the relative cost of the alternative. A sensitivity analysis in the range of 100 - 300 $/kg showed that the conclusions cited in this article remained valid.

Comparison of alternatives brought about a typical problem of comparing a more costly arm with higher productivity to a less expensive one with lower productivity. It becomes even more complicated taking into account three factors:

* the cost of the alternative is relative;
* the data about the potential benefits can only be roughly assessed at this early era of construction automation; and
* a complete cost/benefit calculation is long and tedious, and would have not been possible to use in this research for practical purposes.

Therefore to solve this dilemma, a simple approach was employed, which is to compare the robot's cost of use per unit of work. For example, comparing two alternatives for spraying would be based on the cost of using the alternative, in \$ per m^2 of sprayed area. The parameters for such a calculation were the ones which differed among the alternatives, namely:

C - the relative cost of the alternative;
N - the economic life of the robot;
L - the salvage value at the end of its economic life;
i - the interest rate;
E - the robot's number of employment hours per year; and
P - the productivity of the alternative, measured with the graphic simulation system.

The missing link for these calculations is the assessment of the links' weight. The following section describes the approach, which allowed relatively quick calculations for such an assessment, assisted by a simple computer program.

3 ASSESSMENT OF THE LINKS' WEIGHT

As in the case of the cost computations, and even more so in this case, the calculations had to be simple, and had to allow a relatively rapid assessment of the weight due to the large number of alternatives which were considered.

Fig. 1 shows the robotic system and the notation of the joints and links.

A simplified model was developed based on the assignments designated for **MPIR**, an analysis of the motions of the arm, and a preliminary estimate of the properties of each link. It was assumed that the properties of the carriage and the ones of the vertical link do not differ significantly among the alternatives. Fig. 2 shows the simplified model for the stability and weight calculations, which consists of two horizontal links l_1 and l_2, and the parameters for the calculations.

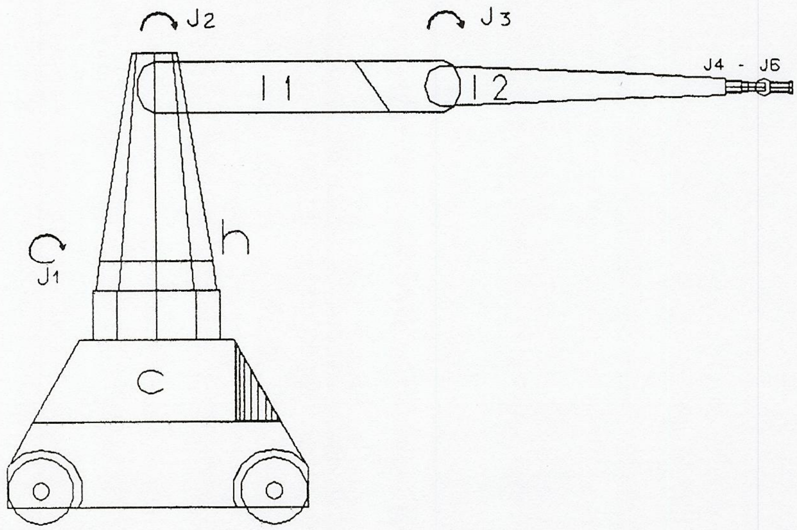

Fig. 1: Robotic System Notation

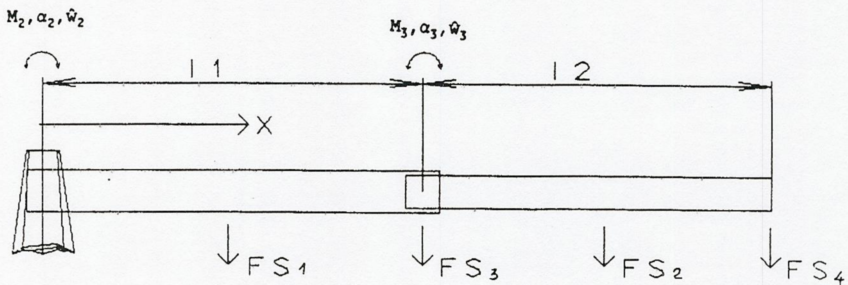

Fig. 2: Model for the Stability and Weight Calculations

FS_1, FS_2 - the weights of links number 1 and 2 respectively.
FS_3 - the weight of the actuator at joint number 3.
FS_4 - the weight of the end effector + the live load + the wrist + the actuators at joints number 4 through 6.
l_1, l_2 - the length of links number 1 and 2 respectively.
α_2, α_3 - the angular acceleration of joints number 2 and 3 respectively.
$\hat{w}_2, \hat{w}_3$ - the angular velocities of joints number 2 and 3 respectively.

The calculations assumed various extreme loading conditions: for example a case in which the arm had been in motion and was suddenly stopped, in various positions, with a maximum deceleration (or started motion with maximum acceleration).

The linear acceleration, a, of a point x distance from the axis of rotation is expressed as:

$$a = 2*\pi*x*\alpha^{o}/360. \tag{4}$$

Also, adding the dynamic effect of the static loads, FS, the force acting on that point, F, is expressed as:

$$F = (1+a/g)*FS \tag{5}$$

where:
g - gravity.

The stresses and deflections were then calculated and compared to the allowed values, based on the properties of the assumed materials and required accuracies.

The maximum stress of link number 1, σ_2, is:

$$\sigma_2 = [F_4*(l_1+l_2) + F_2*(l_1+l_2/2) + F_3*l_1 + F_1*l_1/2]/S_1 \tag{6}$$

where:
S_1 - the section modulus of link number 1.

The maximum stress of link number 2, σ_3, is:

$$\sigma_3 = (F_4 + F_2/2)*l_2/S_2 \tag{7}$$

where:
S_2 - the section modulus of link number 2.

The maximum deflection at the end of the arm, δ, is:

$$E*\delta=[l_{13}*(F_1+8*(F_2+F_3+F_4))+(6*F_2+12*F_4)*(l_2*l_{12}+2*l_{222}*l_1) + l_{12}*l_2*(12*(F_2+F_3+F_4)+3*F_1)+1.5*F_1*l_1^3]/(24*I_1) + l_2^3*(5*F_2+16*F_4)/(48*I_2) \tag{8}$$

where:
E - the Young's modulus of elasticity.
I_1, I_2 - moments of inertia of links number 1 and 2, respectively.

Each cycle of the weight calculations had the following steps:

(1) Cross section assumption for links number 1 and 2.
(2) Assumption of the motors at joints number 2 and 3.
(3) Calculation of the links' properties (weight, moments of inertia, etc.).
(4) Calculation of the equivalent loads, F.
(5) Calculation of stresses and deflections.
(6) Comparison of stresses and deflections to the desired values. If they are equal, move to the next step (7); otherwise go back to the first step (1).
(7) Check of the assumed motors' ability to develop the calculated

torques, velocities and accelerations. If they are not able to do so, go back to step (2), otherwise go to step (8).
(8) Calculation the relative cost of the alternative.

The above process requires many iterations, for each of the numerous alternatives. Consequently, a simple computer program was developed to assist the laborious manual calculations. A very welcomed by-product was that most of the potential errors associated with manual calculations were avoided.

This process was used for calculating the weight and cost of the various alternatives, as well as for calculating the robot's stability in different situations.

4 CONCLUSIONS

The development of the Multi Purpose Interior Robot (**MPIR**) [3,6,7] included an optimization process, which scrutinized a large number of alternatives. Comparing alternatives at the conceptual design stage, when so many of **MPIR**'s parameters were not known, introduced problems not normally encountered with the development of industrial robots. These problems were:

* analysis of the weight of the robotic system, which is limited by the load bearing capacity of the slabs;
* calculation of the stability of the robot during operation; and
* assessment of the robot's cost.

An approach for quickly evaluating the weight of the robot's arm was shown. This approach was based on a simplified model of the robot's arm, taking into account the dynamic impact of the motion. A comparison of the calculations' results to those resulting from traditional methods, was satisfactory. The analysis of the arm's weight was used for calculating the weight of the various alternatives, their stability, and their relative costs.

The alternatives' relative cost was one criteria of the optimization process. The method for assessing this cost, which was shown in this article, allowed practical comparison of alternatives. The comparison between alternatives, which differ in cost and productivity, was performed in terms of the cost of using the robot per unit of work.

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