Optimal Design of a Two Degree of Freedom Manipulandum for Human Motor Control Studies

Antony J. Hodgson

Department of Mechanical Engineering, University of British Columbia
Vancouver, BC, Canada V6T 1Z4 ahodgson@mech.ubc.ca

Abstract – Perhaps the most common configuration for planar manipulandums used in motor control studies is the serial five-bar linkage, but this design suffers from strongly directional inertia and force production characteristics. An alternative parallel-link design whose properties are less direction-sensitive across the workspace has been used in wrist-motion studies, but has never been scaled up for full arm experiments. This paper describes how this design can be optimized for human arm movement studies based on three criteria: workspace size, workspace shape, and minimum force-to-torque ratio.

INTRODUCTION

To understand how humans control their arms while performing complex motor tasks, we must not only measure the kinematics of the interaction (i.e., the positions and velocities of the arm and any object it is handling), but the impedances of the subject and object as well. If the subject is handling actual physical objects, then a perturbation device such as an airjet can be used to estimate the impedances of the subject and object [1]. If we wish to vary the properties and characteristics of the handled object, however, we might consider using a haptic device (a special form of robot) to create virtual objects because it would be simpler to vary the object’s properties in the experimental setting without providing the subject with any other sensory cues (e.g., visual) as to the changes in the programmed behaviour [2].

A popular design for two degree of freedom planar devices is the five-bar serial linkage shown in Figure 1. In contrast to more conventional robotic designs in which the motors and gearboxes are mounted at the joints, this design places both drive motors at the base of the robot in order to reduce the effective endpoint inertia. Unfortunately, the inertia ellipses exhibit large variations in size, aspect ratio and orientation across the workspace, which is undesirable for motor control studies because the varying inertial behaviour can affect the way subjects perform the task being studied.

To minimize the consequences of these inertial effects, Hayward [3] proposed a five-bar parallel linkage (Figure 1) and demonstrated that this design exhibits significantly less inertial variation. Hayward originally developed this device to study wrist and hand motions, and it has not yet been scaled up for full arm motions. In this paper, we assess and optimize the design tradeoffs involved in scaling up the design.

METHODS

Although the position dependence of the manipulability matrix is an important reason for selecting the parallel design over the serial, it is not the most important factor in optimizing the design. Since the robot is to be used for motor control studies, the most important considerations are the workspace size and the interaction forces which can be generated.

A commonly studied motor task is point-to-point movements of ~50 cm, so a suitable workspace would be an ellipse of somewhat larger length and a width of roughly 25 cm (i.e., an aspect ratio of ~0.5).

The maximum interaction force is a particularly important criterion for designing this machine because the torque available from the motors is quite limited in comparison with standard robotic motors. The reason for this is that the nonlinear dynamics associated with geartrains greatly complicate our ability to produce a desired impedance response from our robot, so we would prefer to use direct-drive motors to avoid introducing transmission dynamics. Existing direct-drive manipulandums typically have force-to-torque (F/T) ratios on the order of 2 N/Nm, which is acceptable for this class of studies. However, since the F/T ratio varies with workspace location and since we are interested in the global performance of the device, we must define a performance measure based on the distribution of F/T.
ratios across the workspace. We have found that the area-weighted mean of a score based on the minimum F/T ratio at each point is a useful index of this global performance.

The design variables are the three link lengths shown in Figure 1: the base, the upper arm, and the forearm. The composite score for a proposed design is based on a weighted sum of scores related to the three performance criteria of workspace length, workspace aspect ratio, and F/T ratio. As inputs to the design process, we define three values for each criterion, as shown in Figure 2: (1) a target performance level, (2) a transition width, and (3) a relative weight. The optimization process itself is a straightforward unconstrained multidimensional minimization which was performed using a simplex method.

RESULTS

The design inputs we selected are shown in Table 1, and the corresponding optimal design is shown in Figure 1. The composite score for this design was 81%, which indicates that all of the design criteria were substantially met. As compared with our target performance criteria, we obtained a somewhat larger and wider workspace and slightly better F/T ratios than we had originally hoped. The optimal design will, of course, have differing link lengths if any of the design inputs are changed. In a sensitivity analysis, we systematically varied each of the nine design inputs and found that, since the F/T ratio is the most severe restriction (as indicated by the 71% subscore), the optimal link lengths are roughly inversely proportional to the requested F/T ratio. The optimal link lengths are relatively insensitive to significant (~20%) changes in the other two target inputs.

CONCLUSIONS

In the design approach outlined here, a designer specifies the desired performance levels for a five-bar parallel linkage and then obtains an optimal selection of link lengths. We proposed a technique for converting a point-specific performance criterion (F/T ratio) into a global performance criterion. Although inertial behaviour was not explicitly considered in this formulation, it could be included simply by adding it to the list of performance criteria and modifying the relative weights appropriately. For studies of full arm motions in workspaces on the order of 50 x 25 cm where one wishes to produce interaction forces on the order of 2 N/Nm, the link lengths should be roughly 35 cm at the base, 35 cm for the upper arm, and 65 cm for the forearm.

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REFERENCES

A variety of important studies in the field of human motor control require human subjects to interact with objects exhibiting a range of mechanical behaviours. During these interactions, it is often essential to perturb subjects in order to estimate their mechanical impedances. A robotic arm is commonly used for this purpose because it can emulate complex interactive effects and can measure both force and position during an interaction. Perhaps the most popular configuration currently used is a pantograph.

The nonlinear dynamics associated with geartrains or other transmissions, it is easiest to use direct drive motors to convincingly emulate certain virtual objects (e.g., hard contacts). The pantograph is optimized initially using three criteria: size of the workspace, eccentricity of the workspace, and minimum magnitude of the force-to-torque ratio. The pantograph kinematics are defined by a 3-vector of link lengths: the base (ground) link, the upper arm links and the forearm links (the latter two occur in matched pairs). This vector is called Ls in the M-files described here.

Force/torque important because of need for direct-drive motors.

**Optimization Process**

The main routine which attempts to optimize the design is called `panto.m`. This function may be passed an initial guess at the optimal link lengths and it returns the optimal lengths found. It is also passed (required) a vector of weights to be assigned to the various components of the score.

`Panto` calls an optimization function to determine the best ellipse.

**The M-Functions**

```matlab
function Ls = panto(W,Ls)
function A = ellarea(e,Ls)
% finds the area of the ellipse of the given eccentricity which fits within
% the pantograph limits
function f = elfunct(r)
% Inputs: r a vector of input radii
% Output: f the inner part of the integral evaluated at each radius r(i)
function f = elfunct(q)
% Inputs: q a vector of input angles
% Output: f the inner part of the lower integral evaluated at each angle q(i)
function z = elltan(x,Ls,e)
% Used to find the point where an ellipse is tangent to the workspace bounds
% of a pantograph.
% x is the x coordinate of the current guess at where the ellipse is tangent
% Ls is the 3-vector of link lengths
% e is the eccentricity of the ellipse
% z is a measure of which side of the tangent point we're on (goes to zero at tangency)
function q = pangles( x, Ls )
% finds the pantograph angles corresponding to the given cartesian coordinates and link lengths.
function d = pdistanc( q, x, Ls )
% Used by PANGLES.M. Returns the distance^2 from the endpoint location
% of the pantograph with link lengths Ls and input angles q to the position x.
function J =pjacob( q, Ls )
% Computes the jacobian of the pantograph at the given angular coordinates.
% Inputs:
% q a two-vector describing the angles of the first two links
% Ls the lengths of the base and each of the two links
% Output: J a 2x2 matrix
function [] = pltlimit(Ls)
% Plots the limits of a pantograph with the specified link lengths
% and inscribes into it an ellipse of the eccentricity which gives
% the greatest area.
function f = pmeasure(x)
```

1 In contrast to traditional position-controlled robots, the feel of an interaction device is crucial to its operation and the nonlineairities (such as backlash) in transmissions have particularly detrimental effects on feel.