Optimal Fault Tolerant Control of Flexure Jointed Hexapods for Applications Requiring Less than Six Degrees of Freedom

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Abstract

When less than 6 degrees-of-freedom (DOF's) are required (in precision pointing tasks, for example), the kinematic redundancy of a Stewart platform (or hexapod) makes it possible to implement fault tolerant algorithms. When one or several of the platform legs (struts) fail, methods are presented in this paper for finding a new, reconfigured control to maintain performance.

1 Introduction

Flexure jointed hexapods are great candidates for micro-precision applications. They consist of a base, a payload, and six struts which can change their lengths. The struts, which have spherical joints at both ends, connect the payload to the base. The kinematic redundancy of a Stewart platform (or hexapod) makes it possible to implement fault tolerant algorithms for applications which do not require 6 DOF's. In a robot system, a common failure is due to actuators. Control algorithms tolerant to actuator failures are investigated by McInroy [1] and Noura [2]. This paper builds on the prior work in [1] by expanding the utility of the algorithms through optimization techniques. The reconfiguration algorithm for failed struts developed by McInroy et al. [1] uses the ODOF's to compensate for failures. The ODOF's are a set consisting of the Cartesian directions not required for nominal operation.

This work introduces new optimal solutions suitable for a variety of applications. Experimental results on the University of Wyoming (UW) hexapod are provided which substantiate these conclusions. Due to the page limitation of this publication, only the details of the first optimal solution are described here. A complete report detailing all four solutions can be obtained at the following Web location:
`http://wwweng.uwyo.edu/electrical/hexapod/CDCOptimal.pdf`

2 Fault Tolerant Control Strategy

Figure 1 shows a block diagram of the pointing control system implementation. The plant is decoupled into two independent SISO subsystems. When failures are detected, the nominal decoupling matrix is replaced, using the reconfiguration algorithm. The decoupling matrix is based on the hexapod's Jacobian matrix. The Jacobian matrix, J, relates changes in the Cartesian pose, χ, to changes in the strut lengths, l [3]:

$$\partial l = J \partial \chi \tag{1}$$

where χ is a 6×1 vector of payload plate translations and rotations.

The algorithm derived in [1] is first briefly outlined. Define the number of active DOF's as r. A subvector of χ consisting of the active DOF's is placed into a vector ρ, where $\rho = [\rho_1, \rho_2, \ldots, \rho_r]^T$. The nominal $6 \times r$ decoupling matrix then is a submatrix of J and consists of the columns of J corresponding to ρ.

$$\partial l = D \partial \rho \ . \tag{2}$$

Also, let $\rho_{num} = [\rho_{num_1}, \rho_{num_2}, \ldots, \rho_{num_r}]^T$ be the vector of element numbers corresponding to ρ. For s strut failures, this algorithm allows motion in s ODOF's. Define $d = [d_1, d_2, \ldots, d_s]^T$ as a vector of failed strut numbers, where $d_i \in \{1, 2, \ldots, 6\}$. Define $u = [u_1, u_2, \ldots, u_s]^T$ as the vector of active ODOF's (i.e., allowed to move to compensate for the non-movement of failed struts), and $u_{num} = [u_{num_1}, u_{num_2}, \ldots, u_{num_s}]^T$ as the vector of element numbers corresponding to u. If the active ODOF's are chosen so that $J(d, u_{num})$ is invertible, a new decoupling matrix (3) is developed in [1] which provides accurate orientation of the payload in the active DOF's despite the presence of s failed struts,

$$\begin{aligned} D &= \begin{bmatrix} J(a, \rho_{num}) & J(a, u_{num}) \end{bmatrix} \\ &\quad \times \begin{bmatrix} I \\ -J^{-1}(d, u_{num}) J(d, \rho_{num}) \end{bmatrix} \end{aligned} \tag{3}$$

where a corresponds to the active DOF's, i.e., $a = \{1, 2, \ldots, 6\}$ for the 6 DOF hexapod. Note that, by equating the number of failures and active ODOF's, $J(d, u_{num})$ is square.

3 Optimal Selection of Active ODOF's

In [1] the selection of ODOF's is arbitrary. In gross motion Stewart platforms, the Jacobian matrix changes significantly across the range of its workspace. Flexure jointed hexapods, in contrast, have a very small workspace, and correspondingly small Jacobian changes. For each combination of strut failures, a corresponding optimal combination of ODOF's can be found.

[1] This work was supported in part by the BMDO and ARO under Grants DAAG55-98-1-0007 and DAAH04-96-0457

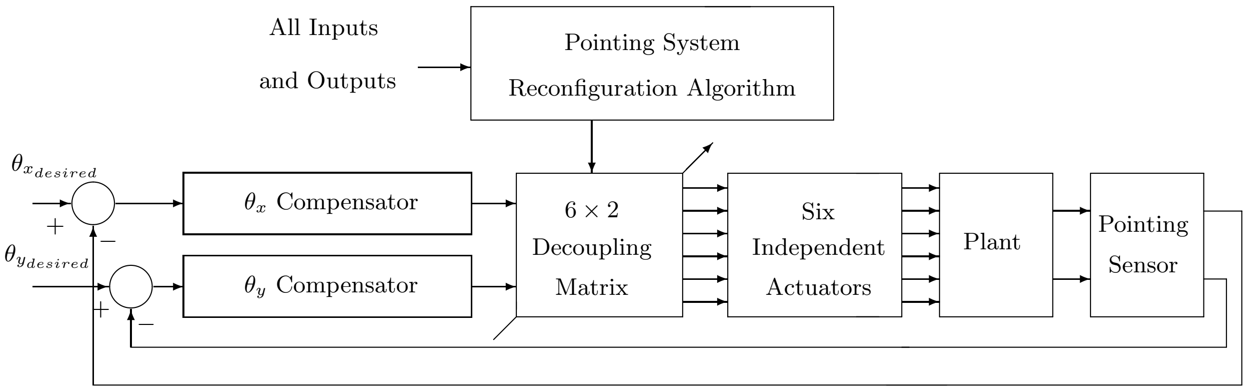

Figure 1: Reconfigurable control strategy

The optimization is based on the condition number, the maximum, and the minimum singular values of the Jacobian matrix. The selection of a particular set of ODOF's can be optimized with different criteria for different applications.

3.1 Optimal ODOF's Based on the Condition Number of the Decoupling Matrix

When the condition number of the hexapod Jacobian is minimal, so also is the difference of required joint effort for achieving velocities of the payload in different desired directions. Thus, the minimum condition number corresponds to an optimal selection of ODOF's. The optimization problem then becomes

$$\min_{u_{num}} cond(D) \tag{4}$$

The analytical solution to this problem is intractable, but the problem can be solved efficiently by exhaustive searches. Because J is essentially constant for flexure jointed hexapods, the search can be completed off-line and only need be completed once.

4 Experimental Results

The optimization algorithms have been experimentally verified on the UW hexapod. To compare these algorithms, the UW hexapod was used to track a large spiral while struts 2 and 3 were disabled. The spiral θ_x -θ_y pattern is a realistic command used, for example, to search for a target while trying to acquire its signal. The UW hexapod is currently equipped with sensors for measuring Cartesian rotations about the "x" and "y" axes. Figure 2 shows the experimental results on the UW hexapod for four cases: the nominal case; the failed case without correction; the failed case using 2 optimal ODOF's; and the failed case using 4 ODOF's. By examining the root mean square (RMS) average errors in each case, the system performance is readily compared. The uncorrected system displays a marked degradation in performance. The performance of the corrected system is similar to the case with no failures. If all the ODOF's are picked, the RMS average errors are reduced by 19.7% in θ_x direction and 7.5% in θ_y direction. The error is also averaged along these two directions. Compared to the nominal case, there is also an improvement of about 9%.

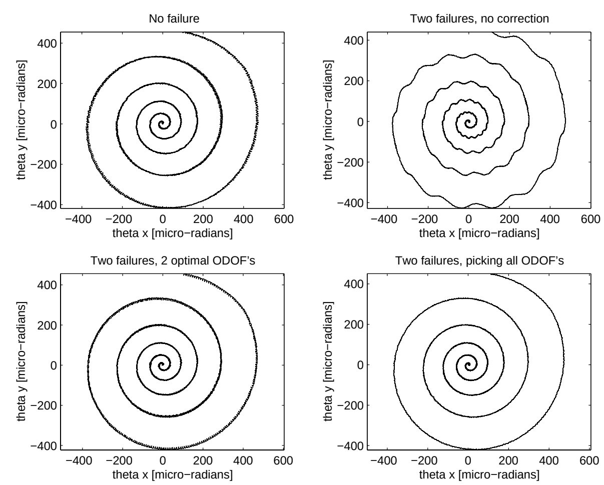

Figure 2: Tracking spirals with and without correction

References

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