A Fault Tolerant Joint Drive System for the Space Shuttle Remote Manipulator System

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Abstract

An analysis of an improved joint drive system for the Shuttle Remote Manipulator System (SRMS), capable of sustaining a single actuator failure, is presented. This proposed system employs a differential gear train with dual input actuators driving a single load. The mathematical model for the drive system includes: gearbox flexibility and damping, motor damping, high gear ratio, and high load impedance. Surprisingly, the non-linear dynamic equations for the system reduce to linear form without approximation. Effects of gearbox placement and load sharing are examined. A feedback system that improves overall response is discussed. Simulation results show that the design is able to sustain a single electromechanical actuator failure without impeding the joint's performance. Plans for a hardware implementation to verify the system are given.

1. Introduction

NASA is constantly investigating design modifications that will enhance performance for both the Space Shuttle Remote Manipulator System (SRMS) and future Space Station Freedom (SSF) robotic systems. The SRMS has played a critical role in past space shuttle missions, and it along with additional robot manipulators will be heavily relied on for SSF construction and maintenance. To this end, each robotic system must be made sufficiently redundant to withstand at least one failure without degrading operational performance.

The SRMS is the 6-DOF arm portion of the Shuttle's Payload Deployment and Retrieval System (PDRS) (Figure 1). The SRMS is used to grapple a payload in the cargo bay and then release it at the deployment position, or conversely, to capture a free-flying payload and berth it in the cargo bay. Each of the SRMS's six joints is driven by a single identical, reversible, brushless DC motor. The drive trains for all joints are similar, except for the gear ratio. Each drive train is based on a single chain design and is not fault tolerant to an electromechanical actuator failure.

The SRMS has a manual backup mode which can be used to perform a stowaway execution in the event of certain failures, but it is only designed to be fail-safe, and not fault tolerant. This limitation has led to the proposal of several manipulator design modifications. Chladek [1] describes multiple actuator concepts and redundant degree of freedom manipulators. A dual actuator mechanism with staged epicyclic gear train is under development by the University of Texas [2].

A dual input, one output differential is proposed as a fault tolerant joint drive candidate and examined here. A differential is a bevel planetary train with equal sun gears, constituting a summing mechanism. The arrangement allows the two input motors to run at different speeds. If one of the differential's inputs fails, it can be deactivated, and the system can continue to meet operational requirements in a single input mode.

Two versions of a dual drive differential system, one with two high ratio gearboxes before the differential and one with a high ratio gearbox after the differential, are compared. Non-linear dynamic equations for both systems are derived and then converted to linear state equations without approximation. An evaluation of open loop system characteristics leads to a controller design with rate feedback. The effect of varying the load sharing between the two input drives is analyzed, and a failure is simulated. Finally, a motor backdrive limiter is proposed to improve failure response and reduce adversarial tuming between the input motors.

Notation

B viscous friction coefficients
Gx, Gy load sharing from actuator x, y
J moment of inertia
K gearbox stiffness
Kd joint speed feedback gain
Kvx, Kvy motor x, y speed feedback gain
Kx_s, Ky_s gearbox stiffness for actuator x, y
L load; load gear
m, n driving gear of actuator x, y
NL gear ratio of load gear to differential output gear
Nx, Ny gear ratio of differential input gear to driving gear of actuator x, y
p differential output shaft
Tx, Ty motor x, y driving torque
Wx(0), Wy(0), Wx0, Wy0 input speed, joint speed
Wx(1x), Wy(1y) motor x speed
Wn(0), Wn(1) gear m speed for model 2
Wn(0n) gear n speed for model 2
x, y first, second motor module
1, 2 input gear, differential sun gear of actuator x, y
3 differential output gear
η gearbox power transmission efficiency
ηF,B gearbox forward driving, backdriving efficiency

Figure 1. Shuttle RMS configuration (Courtesy of Spar Aerospace Limited, Toronto, Ontario, Canada).

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2. SRMS parameters

The SRMS is a 50 foot long arm with six joints providing movement of the arm within joint limits. When the SRMS has a large payload, its velocity is severely limited; with a 32,000 lb payload attached, the maximum drive speed of the end effector does not exceed 0.2 ft/sec. At this speed, the SRMS can bring the payload to a stop within 2 feet in approximately 40 seconds [3].

The performance of the shoulder yaw joint is analyzed, since it represents the most demanding case among the six joints. The shoulder yaw joint has the most compliant gearbox, largest gear ratio and sees the greatest effective inertia. The parameters used in this analysis were obtained from references [4,5], and are listed in table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear ratio</td>
<td>1842</td>
<td></td>
</tr>
<tr>
<td>Moment of inertia of motor rotor and input shaft of gear box</td>
<td>0.0002</td>
<td>slug-ft-ft</td>
</tr>
<tr>
<td>Effective load inertia with a 32,000 lb payload attached and the arm in its fully extended configuration</td>
<td>3,620,000</td>
<td>slug-ft-ft</td>
</tr>
<tr>
<td>Gearbox stiffness as measured from the motor side</td>
<td>9.95</td>
<td>slug-ft-ft</td>
</tr>
<tr>
<td>Motor module viscous friction</td>
<td>0.3748</td>
<td>ft-lb/sec</td>
</tr>
<tr>
<td>Motor maximum driving torque</td>
<td>0.5239</td>
<td>ft-lb/sec</td>
</tr>
<tr>
<td>Maximum joint rate, with baseline 32,000 lb payload attached</td>
<td>0.004</td>
<td>rad/sec</td>
</tr>
</tbody>
</table>

Table 1. Major parameters of the SRMS's shoulder yaw joint

3. Proposed fault tolerant mechanism

An ideal fault tolerant dual drive actuator is a double sided symmetric mechanism with an independent controller for each side constituting a two input, one output redundant mechanism. When a failure occurs on one side, the other side will pick up the whole load, and continue the present task without degrading system performance. Could a differential drive joint support this requirement? Two different mechanism arrangements of a differential gear train with gearboxes, motors and payload are evaluated.

3.1 Model 1: motors-differential-gearbox-load

Model I includes two driving motor shafts directly coupled to each input shaft of the differential, and the output ring gear is meshed with a high ratio speed reducing gearbox to drive the robot arm and the attached payload. In such an arrangement, the differential runs at a high speed, and the gearbox and the arm flexibility are modeled in the gearbox spring constant. The mechanical modeling is shown in Figure 2.

![Diagram of Model 1: motors-differential-gearbox-load](image)

Figure 2. Model 1, motors(q,y)-differential(3,2)-gearbox(3,1)-load(0), a torsional spring is modeled at the input side of gearbox(3,1).

The differential gear train has equal sun gears as input gears, yielding the following kinematic equation:

\[
\theta_s = \frac{\theta_x + \theta_y}{2} \tag{1}
\]

Ideal gear trains without backlash are modeled in this analysis (i.e., the arc length of the distance traveled by one gear equals that of the other) and yield the following gear equations:

\[
\frac{\delta_x}{\delta_k} - \frac{\delta_y}{\delta_l} = \frac{N_y}{N_k} - 1 \tag{2}
\]

The expression for transmitted torque across the differential, or the efficiency defined as the ratio of the output power to the input power through two meshed gears, is quite complicated. Sliding losses along teeth, windage losses because of lubricant or even the speed-dependent losses make the efficiency unpredictable. It should be noted that efficiency is dependent on such factors as the gear ratio, the material's coefficient of friction, the depth of cut, the pressure angle of teeth, type of meshing, and the nonlinear behavior of forward and back driving resistances. The following equations are for an idealized inertial, viscous friction, gear stiffness model with a 100% transmission efficiency, η:

\[
\frac{N_{T_{1,2}}}{N_{1,2}} - \frac{U_{1,2}}{B_{1,2}} - \frac{N_{T_{1,2}}}{U_{1,2}} - \frac{B_{1,2}}{B_{1,2}} = K \left( \delta_x - \delta_y \right) \tag{3}
\]

Conservation of energy holds at any instant of time and leads to the power equation:

\[
\begin{align*}
\tau_1 \delta_1 + \tau_2 \delta_2 - J_1 \delta_1 + J_2 \delta_2 &= J_1 \delta_1 + J_2 \delta_2 + J_1 \tau_1 + J_2 \tau_2 + B_1 \delta_1 + B_2 \delta_2 + B_3 \delta_1 + B_4 \delta_2 + B_5 \delta_1 + B_6 \delta_2 + B_7 \delta_1 + B_8 \delta_2 + \frac{K (\delta_x - \delta_y)}{2} \tag{4}
\end{align*}
\]

By defining \( \delta_{1,2,3,4,5,6,7,8} \), \( \delta_x, \delta_y, \delta_z, \) and \( \delta_3 \) as system state variables, equations (1) through (5) may be transformed, without approximation, to a time-invariant linear system with two inputs and seven state variables. The state equations in matrix form are:

\[
\begin{bmatrix}
\dot{\delta}_1 & \dot{\delta}_2 & \dot{\delta}_3 & \dot{\delta}_4 & \dot{\delta}_5 & \dot{\delta}_6 & \dot{\delta}_7 & \dot{\delta}_8 \\
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\delta_1 & \delta_2 & \delta_3 & \delta_4 & \delta_5 & \delta_6 & \delta_7 & \delta_8 \\
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{2N_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{2N_2} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{J_1} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{J_2} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{J_3} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{J_4} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{J_5} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{J_6} \\
\end{bmatrix}
\begin{bmatrix}
\tau_x & \tau_y \\
\end{bmatrix}
\]

where \( J_1 = J_2 = J_3 = 0 \), \( J_4 = J_5 = J_6 = J_7 = J_8 = N_1^2 \), \( B_1 = B_2 = B_3 = B_4 = B_5 = B_6 = B_7 = B_8 = 0 \), and \( N_1^2 = N_2^2 \).
3.2 Model 2: motors-gearboxes-differential-load

An alternative mechanism arrangement consists of placing a gearbox in front of each input shaft of the differential as shown in Figure 3. In such an arrangement, the differential operates at lower rotational velocities and accelerations and is, therefore, expected to have a longer useful life. But, the system cost and complexity increase with the addition of another gearbox. For the SRMS, essentially all the arm flexibility arises from the high ratio gearboxes. Therefore, the spring characteristics of this system are modeled as part of the gearbox, and for this model results in two equal springs prior to the differential.

This system yields the following kinematic equations:

\[
\dot{\theta}_1 = \frac{\dot{\theta}_1 + \dot{\theta}_2}{2}
\]

\[
\dot{\theta}_2 = \frac{\dot{\theta}_1 + \dot{\theta}_2}{2} - J_1 - N_x
\]

\[
\dot{\theta}_3 = \frac{\dot{\theta}_1 + \dot{\theta}_2}{2} - J_2 - N_y - 1842
\]

\[
\dot{\theta}_4 = \frac{\dot{\theta}_1 + \dot{\theta}_2}{2} - J_3 - N_y - 1842
\]

Torque equations:

\[
T_x = (J_1 + B_1 \theta_1) - J_2 \theta_2 - J_3 \theta_3 - J_1 \theta_4
\]

\[
T_y = (J_1 + B_1 \theta_1) - J_2 \theta_2 - J_3 \theta_3 - (J_1 + B_1 \theta_4)
\]

\[
N_x \theta_2 (\theta_2 - \theta_3) - N_x \theta_3 (\theta_2 - \theta_3) - N_x \theta_4 (\theta_2 - \theta_3) - N_x \theta_5 (\theta_2 - \theta_3)
\]

Power equation:

\[
T_x \dot{\theta}_1 + T_y \dot{\theta}_2 - J_1 \theta_1 \dot{\theta}_1 + J_2 \theta_2 \dot{\theta}_1 + J_3 \theta_3 \dot{\theta}_1 + J_4 \theta_4 \dot{\theta}_1 + J_5 \theta_5 \dot{\theta}_1
\]

\[
- J_1 \theta_2 \dot{\theta}_2 + B_1 \dot{\theta}_1 + B_1 \dot{\theta}_2 + B_1 \dot{\theta}_3 + B_1 \dot{\theta}_4 + B_1 \dot{\theta}_5 + B_1 \dot{\theta}_6
\]

\[
- K_1 (\theta_2 - \theta_3) (\theta_2 - \theta_3) + K_2 (\theta_2 - \theta_3) (\theta_2 - \theta_3) (\theta_2 - \theta_3)
\]

4. Open loop characteristics

Using the existing SRMS shoulder yaw joint assembly as a guide, low moments of inertia \(j_1=j_2=j_3=0.0007 \text{ slug-ft-ft} \) are assigned to the bevel gears in model 1. The proposed differential gear train in model 2 is on the output side of the gearboxes, and consequently, has a larger radius and is expected to sustain a much higher torque load during operation. The moments of inertia for this bevel gear set are estimated at \(j_1=j_2=j_3=10 \text{ slug-ft-ft} \).

Calculated from the system matrices in equation (6) and (13), the open loop eigenvalues for both models are displayed in Table 2. The motors’ minimal viscous friction yields pairs of system poles very close to the imaginary axis, resulting in lightly damped systems. Rate feedback is next added to increase system damping.

<table>
<thead>
<tr>
<th>model 1</th>
<th>model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-0.9640 + 25.3667i)</td>
<td>(-0.0199 + 36.0436i)</td>
</tr>
<tr>
<td>(-0.9640 - 25.3667i)</td>
<td>(-0.0199 - 36.0436i)</td>
</tr>
<tr>
<td>(-1.9256 + 0.0000i)</td>
<td>(-1.9256 - 0.0000i)</td>
</tr>
<tr>
<td>(-2.5564 + 0.0000i)</td>
<td>(-2.5564 - 0.0000i)</td>
</tr>
<tr>
<td>(-0.0000 + 0.0000i)</td>
<td>(-0.0000 + 0.0000i)</td>
</tr>
</tbody>
</table>

Table 2. Open loop eigenvalues of models 1 and 2.
5. Addition of a feedback controller

The joint level servo for the current SRMS is operated in either position hold mode or joint rate mode. When the position hold mode is activated, a position loop is closed around the servo maintaining the current joint angle setting. For the operation under rate mode, the SRMS control algorithm converts the hand controller input commands into resolved output rate commands for each joint, so that the end effector or payload follows the commanded trajectory. Operations under rate mode when the manipulator is in motion represent the more critical cases and are examined here.

The open loop results make it clear that both models require feedback compensation integrated into the servo controller to improve system damping. A simple servo system having tachometer feedbacks from both the output shaft and the individual input shafts is added to each model. The rate control equation for each actuator is represented by:

\[
\begin{bmatrix}
T_o & -K_m & 0 & 0 & G_x & K_x \\
T_i & 0 & -K_m & 0 & G_y & K_y
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_1 \\
\dot{\theta}_2
\end{bmatrix}
= \begin{bmatrix}
G_x & G_y
\end{bmatrix} U \tag{14}
\]

where \(U\) : rate command
\(K_m\) : velocity feedback gain from each input shaft
\(G_x, G_y\) : velocity feedback gain from the output shaft
\(K_x, K_y\) : magnitude of contributions between dual actuators

Starting with zero initial states, each model is commanded to move the joint at a constant coarse rate of 0.004 rad/sec. The simulation results with servo gains \(K_v=K_y=0.0005, \ K_d=100\), and equal load sharing: \(G_x=G_y=0.5\), for each model are shown in Figure 4.

For both systems, the input motor responses exhibit lightly damped high frequency motion (25 rad/sec for model 1; 42 rad/sec for model 2). The payload's high inertia combined with the joint's soft gearbox acts like a low pass filter and attenuates this high frequency motion, yielding a smooth joint output response. The open loop results make it clear that both models require feedback compensation integrated into the servo controller to improve system damping. A simple servo system having tachometer feedbacks from both the output shaft and the individual input shafts is added to each model. The rate control equation for each actuator is represented by:

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Motor damping may be increased for both models by increasing the tachometer feedback. The root loci, for equal load sharing, with \(K_v\) and \(K_y\) varying is given in Figure 5. The higher gains increase the damping ratio for the high frequency modes noted above. The very high frequency mode (346 rad/sec) seen in model 2 is not affected. This mode will be discussed in a later section.

![Figure 4a](image1.png) Model 1, equal load sharing, 0.004 rad/sec joint output rate is commanded. There is a steady state error for the joint speed, WL.

![Figure 5](image2.png) Root loci of closed loop system for both models. \(K_v=K_y=0.0005, \ K_d=100\).

6. Load sharing

As shown in equation 14, a differential system permits unequal load sharing between two actuators. With the aid of sensor devices and intelligent software, automatic swapping of the power contributions between the two motors may be supported to enhance the system performance, eliminating backlash and maintaining each motor's temperature within acceptable limits. However, unequal load sharing in the presence of a high load impedance results in adversarial turning and effort canceling backdriving. Essentially, the motors fight each other, since each motor's backdrive impedance is significantly less than the load impedance.

The simulations for 70% to 30% load sharing and 110% to -10% load sharing cases of 0.004 rad/sec joint speed command input are shown in Figure 6. The responses for the two models are alike. In each case, motor \(y\) is backdriven by the external torque contributed by motor \(x\), constituting an overall adversarial turning case. Actually, with such a significant difference between the moments of inertia of driving motor and the effective load inertia, a slightly off equilibrium load sharing is sufficient to produce adversarial turning!

Theoretically, the two motors' contributions may be varied and still produce the same output (WL). One can dynamically vary the torque distribution which affects the total power input, while still maintaining the same output, WL.
The transient response due to a failure is next examined. Representative manipulator joint level mechanism failures for the current SRMS include the following:

1. Open or shorted motor winding;
2. Servo power controller fails on or off;
3. Motor controller fails on or off;
4. Position sensor or velocity transducer failure;
5. Bearing failure such as seizure, increased friction;
6. Gearbox failure such as seizure, increased friction or freewheel;
7. Brake seizure, brake slippage, brake loss;
8. Cabling problems, shorts or opens;

An intelligent fault detection and fault identification system should be included as part of a fault tolerant manipulator system. After a fault occurs, rapid detection is required, so that one simple and fast reconfiguration may take place and allow the continuation of the present task. When one side of the differential fails, that side's input sun gear must be locked up, and its input motor must be disabled quickly, to prevent the system from destroying itself.

A simulation for the case with one motor failing: torque dropping to zero without locking up its actuator, is examined here and shown in Figure 7. The fault transient responses for the two models are similar, and result in a stable joint output speed after failure, for both equal and unequal load sharing. In addition, model 2 (Figure 8) exhibits a very high frequency lightly damped response for both 50%/50% and 70%/30% load sharing.

It should be noted that the fault transient response is not only a function of the controller algorithm (see equation 14) and system dynamic properties at the moment of failure, but is also dependent on the backdrive resistance of the gearbox. The backdrive resistance of a gearbox is addressed next.

8. Backdrive resistance of the gearbox

The following non-linear physical phenomena affect the SRMS's joints motion: motor braking, stiction, and friction, and gearbox backdriving efficiency and backlash. For a fault tolerance study, forward/backdrive efficiencies are the most significant, and must be considered when doing a simulation. Backdrive efficiencies as noted earlier are very important to load sharing and also to failure situations.

Modelling backdrive and forward drive efficiencies changes torque equation (3) for model 1 and equations (9) and (10) for model 2 yielding equation (15), (16), and (17):

\[
\begin{align*}
K(\theta_g - \theta_f) + (J_1 + B_1 \delta_1) + u(\theta_d, t) \quad & \text{if } \text{motor } x \text{ forward driving} \\
= \frac{1}{n_{m1}}N_1 + u(\theta_d, t) \quad & \text{if } \text{motor } x \text{ backdriving} \\
\frac{n_{m2}}{n_{m1}}N_2 + u(\theta_d, t) \quad & \text{if } \text{motor } y \text{ forward driving} \\
= \frac{n_{m2}}{n_{m1}}N_2 + u(\theta_d, t) \quad & \text{if } \text{motor } y \text{ backdriving}
\end{align*}
\]
These equations reveal that forward efficiencies of less than 1 will increase the torque required to accelerate the inertia load or overcome an external torque load. Therefore, a high forward efficiency is always desired. However, a low backdrive efficiency (high backdrive resistance) could be a desirable feature in a fault tolerant differential drive design. If the transmission is not backdriveable, such as when a worm gear is meshed with a worm wheel, torque cannot be transmitted back to the motor. Examine equation (17) as an illustration: when motor y fails with $\tau_y$ dropping to zero, but is still free to spin, $\eta_{B_F}$ and $(6y - \epsilon_{ln})$ will be opposite in sign, and the backdriving mode will engage, preventing motor y's speed from running away.

With this low backdriving efficiency feature, the adversarial turning problem owing to the high output to input inertia ratio is significantly reduced (Figure 9). However, with this system the gears absorb all the backdrive load and gear fatigue becomes an important issue.

![Figure 9. A comparison of the failure transient responses for 100% and 70% backdriving efficiency on Model 1; both cases have 100% forward driving efficiency; 0.004 rad/sec joint output rate is commanded.](image)

9. Conclusion

The current SRMS on the orbiter has been successfully operated during previous shuttle missions, and it is expected to perform on-orbit duties safely and reliably for many more years. To insure this, it needs the capability to sustain any single electromechanical failure and still satisfactorily complete its tasks.

A dual input differential has been proposed as a fault tolerant joint drive system for the SRMS. Two mechanism models that differ in the placement of high ratio gearboxes with respect to the differential have been compared. The open loop characteristics are unacceptable in both cases, and the model with a gearbox behind the differential gives the more desirable response. Acceptable responses have been obtained for both models with the addition of rate feedback. The unequal load sharing used to eliminate backlash can result in severe adversarial backdriving under certain conditions. The adversarial effect can be reduced by using a worm gear/wheel system that limits the backdriving torque.

10. Future work

The simulations covered here were done with the SRMS modelled in its fully extended configuration and simplified as a time-invariant system. It is noted that the SRMS is designed to deploy a 65,000 lb payload, and retrieve a 32,000 lb free-flying payload. The system's performance varies with the payload weight. Also, the coupled motion among the six joints produces a varying effective load inertia. Consequently, in future analysis, the system should not be treated as a time-invariant system and should include the above effects.

A hardware demonstration is planned to validate simulation results. A scaled testbed consisting of motors, gearboxes with and without restricted backdrive gear pairs and a differential will be constructed. A payload simulator will be designed to model load impedance. Fault detection and fault compensation systems will be incorporated. In-line torque sensors will be integrated into the system to detect faults, and may also be used with advanced control concepts, such as feedforward torque control.

Acknowledgement

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References