ACTUATORS FOR A SPACE MANIPULATOR

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ABSTRACT

The robotic manipulator can be decomposed into distinct subsystems. One particular area of interest of mechanical subsystems is electromechanical actuators (or drives). For this paper, we will define a drive as a motor with an appropriate transmission.

This paper will give an overview of existing, as well as state-of-the-art drive systems. The scope is limited to space applications. A design philosophy and adequate requirements are the initial steps in designing a space-qualified actuator. We will focus on the d-c motor in conjunction with several types of transmissions (harmonic, tendon, traction, and gear systems). We will evaluate the various transmissions and key performance parameters will be addressed in detail. Included in the assessment is a shuttle RMS joint and a MSFC drive of the Protoflight Manipulator Arm. We will also investigate compound joints.

Space imposes a unique set of requirements for designing a high-performance drive assembly. Its inaccessibility and cryogenic conditions warrant special considerations. This paper will present some guidelines concerning these conditions. The goal is to gain a better understanding in designing a space actuator.

Introduction

The primary manipulator is usually a serial design of drives and arm structure, but additional work is being done on parallel manipulators. In this paper we will concentrate on the drive, otherwise referenced as the motor/ transmission package.

The manipulator may be a two-link design with the joints separated by arm segments. [1] The first choice to be made is do we want distributed actuators or do we want an integrated design? Distributed actuators afford the capability to be modular, maintainable and easily upgradable. As a result, it sacrifices a compact design and a less-than-optimal inertia distribution. The choice in effect also limits the possible transmission options. We will discuss this more later in this paper.

Space represents several advantages as well as disadvantages for a manipulator. (Refer to Table 1 on design factors for a space manipulator.) Microgravity is favorable because it reduces each joint's torque requirement. The lubricant must be space compatible with low outgassing. Moreover, the materials and process must also be compatible and stable. Thermal management is a major concern with several aids such as passive control through thermal coatings and dynamic control with rod-heaters or tapes.

Table 1   Design Factors for Space Manipulators

HOSTILE ENVIRONMENT	POWER SOURCE	WEIGHT & SIZE	RELIABILITY
-Extreme operating temperatures (-67 F to 437 F is common)	-Electric	-Desire a light and compact design	-Must withstand the launch loads
-Plastics and rubber outgas in a vacuum	-Minimum power consumption is desirable	-A design that can be stored compactly	-A simpler design is reliable
-Micro gravity eliminates weight but not its inertia		-Modular design can be reconfigured to satisfy several requirements	-Design should be based on a mature technology

The mechanisms must be demonstrated under thermal vacuum conditions. The biggest hurdle will be the inaccessibility of the hardware in space. As a result, the manipulator needs to incorporate mature technology with a reputable service life. General longevity is a major concern.

This paper will start with the electric motor and be followed by an review of suitable transmissions. We will look at the particular characteristics that make a good actuator with a design methodology. We will discuss several design considerations for each type of transmission. Finally, we will discuss a compound joint.

Motor

The motors in a space manipulator will be electric instead of hydraulic, hydrokinetic, hydrostatic, or pneumatic. Even though the hydraulic output torque is higher per unit weight than electric, the support equipment (pump, compressor, accumulator, etc) and the potential for leakage make hydraulics undesirable. The use of a DC servo motor is a proven technology. Its usage and installation are very clean. The brushless motor [2] is used for the following reasons:

- Brushless units may be operated at much higher speeds and at full torque at those speeds;

- The stator may be mounted in a substantial heat sink to minimize temperature rise and prolong bearing life;

- The brushless motor does not have the brush wearout or the presence of brush wear particles (debris);

- The electromechanical interference (EMI) normally associated with arcing of the brush-commutator interface is eliminated;

- Where long life is required, the limitation of the motor is increased to match the life expectancy of the bearings;

- Less preparation for a space environment (vacuum operation).

One disadvantage with the brushless motor is the added complexity to the commutation electronics. However, this problem has been worked.

The brushless motor consists of a stator that supports the armature coils and shaft bearings, and a rotor that carries permanent-magnet poles. A typical motor uses Alnico magnets. For the next space application, the magnets used will be from the rare-earth family, probably samarium-cobalt [3]. The rare-earth magnet (samarium-cobalt, Neodymium-Iron-Boron) has a higher maximum energy product rating than commercial magnets like Alnico, as shown in Fig. 1.
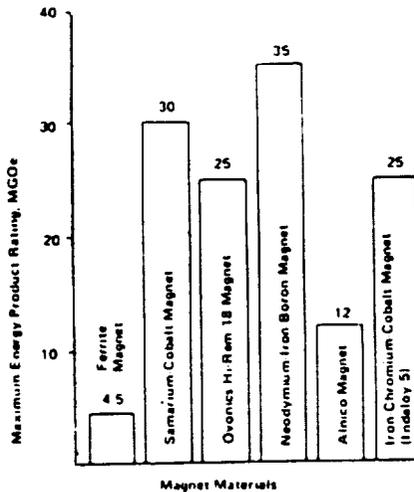

Figure 1   Maximum Energy Product Ratings for Different Magnets

The stronger magnets have a higher airgap flux density, that produces a higher torque for a given volume. Neodymium-Iron-Boron has the potential to produce even greater output torque, but its output has been inconsistent and requires further testing. If the magnets are exposed to temperatures above the magnet cure temperature, there is degraded performance.

The magnets are formed into teeth to accommodate the high flux density. The toothed geometry contributes to high inductance and high iron losses. As a result, the motor has a tendency to cog at low speed. The speed at which cogging is evident is inversely proportional to its pole count. As inductance rises, the transistors that commutate the coils require more current.

The flux levels in the teeth vary as the motor rotates. This causes hysteresis and eddy current lags that may account for more than half of the total losses in conventional brushless motors. It also may cause cogging. One remedy is to skew the orientation of the magnet with respect to the rotor. Unfortunately, this can be costly with difficult manufacturing processes that may result in lower performance.

New motors are being developed to remedy some of these problems. They include: toothless armatures, multipoles, and hybrid motors. The result should be greater performance out of the brushless motors.

Transmissions [4, 5, 6, 7]

The following transmissions to be discussed have applications to robotic manipulators. They are:

1) Direct Drive (no transmission)
2) Traction Drive
3) Harmonic Drive
4) Tendons
    a) Bands
    b) Cables
    c) Chain
5) "Roto-Lok"

6) Gears
    a) Spur
    b) Squirm
7) Torque Tubes
8) Multiple Linear Actuators
9) Linkage
10) Cycloidal Speed Reducers

The majority of the aforementioned transmissions are in use today on commercial as well as research manipulators. This list might not be all-inclusive, but we feel it represents the majority of the available transmission technology today.

Review

Direct Drive [8] - In direct drive, the motor is coupled to the load without any form of mechanical leverage. The result is a simple system without a transmission, as depicted in Fig. 2.
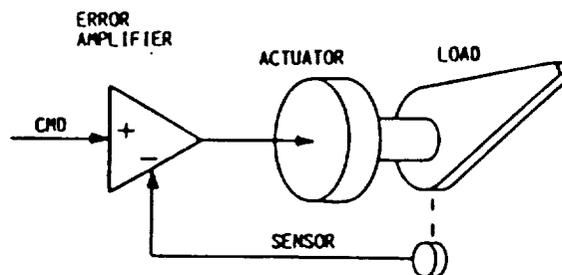

Figure 2 Direct Drive

Takeo Kanade (CMU) and Haruhiko Asada (MIT) have built the first direct drive arm, DD1. CMU has built a second arm, DD2, which is a SCARA design. In the commercial area, Adept Co., Sanyo and United States Robot have used direct drive motors for selected joints.

Traction Drive [9] - Traction drive (Fig. 3) operation is based on the rolling contact between two smooth and unequally sized rollers. The traction forces are transferred via the traction fluid. The normal forces must be large enough to prevent destructive slipping of the rollers. They rely on friction to transport torque.
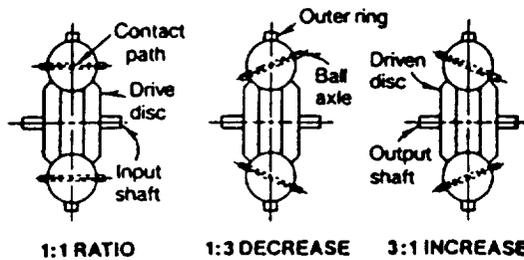
Figure 3 Traction Drive

Harmonic Drive [10] - Harmonic drives in Fig. 4 are precision gear-type
speed reducers. Its design is based on elastic body mechanics as opposed to
rigid body mechanics for conventional gearing. Harmonic drive uses controlled
deflection in the flexspline to reduce speed and multiply torque.
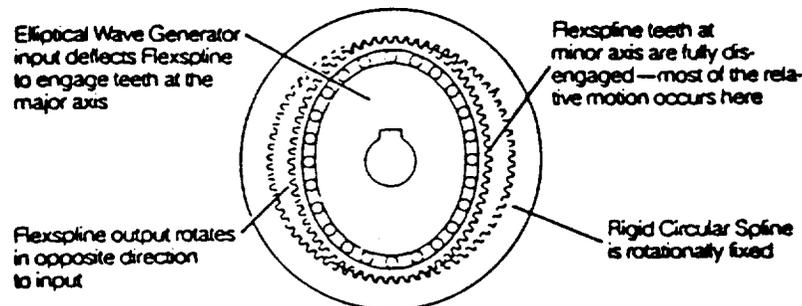

Figure 4 Harmonic Drive

High speed is input into the wave generator. The rigid circular spline is
fixed, while the nonrigid flexspline drives the load at reduced speed. The
wave generator deflects the nonrigid flexspline into an elliptical shape which
meshes the teeth at both ends of the wave generator major axis. Because the
flexspline has two fewer teeth than the circular spline, rotation of the wave
generator produces relative motion between the two splines.

Currently, R. Cipra at Purdue University uses harmonic drives in their
planar arm. NOSC-San Diego uses them in their underwater arm and they are
also used by Telerobotics International and Robotics Research.

Tendons - Under certain circumstances, it would be desirable not to
collocate the axis of actuation and the motor. There are transmission devices
such as cables, belts, bands, and chains to transfer motion from one location
to another. Each transfer device has distinct advantages depending on load,
distance, and size. For example, steel cables are desirable for small robots.
Larger robots use synchronous belts with trapezoidal teeth that fit into
sprocket wheels for positive motion. Roller chains are used for longer
distances than belts. Central Research Laboratories utilizes steel bands to
drive their teleoperated robot in nuclear hot cells. The University of Utah
uses a composite band of kevlar and dacron to power its hand, as in Fig. 5.
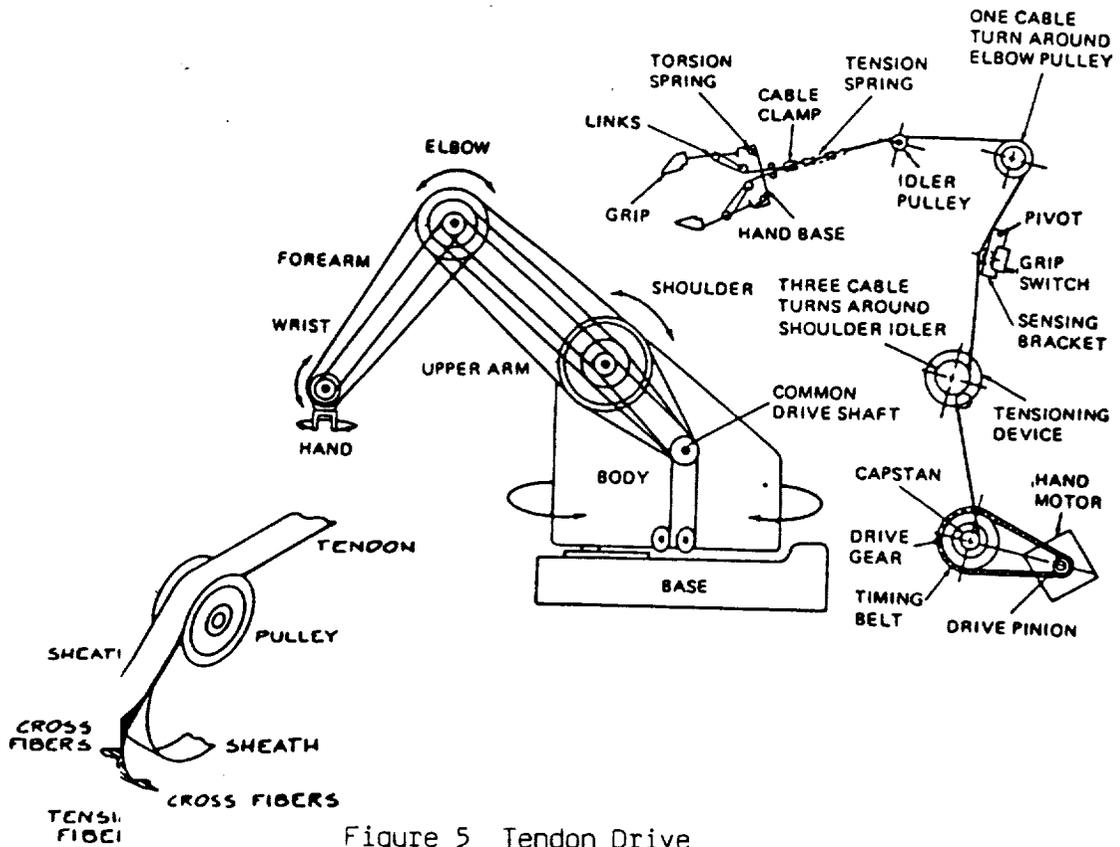
Figure 5   Tendon Drive

Rot 11] - A Roto-Lok drive smoothly couples a drive to a load using standar.ble cables in a figure-eight configuration. This friction-drive technol.patented by TRAX Instrument Corporation. The system uses simple cylindr.apes and spring-compensated cables. Roto-Lok was originally developi critical positioning of astronomical instruments. Each cable is preload. spring so that the driving and driven shafts (cylinders) are linked lpretensioned cable members in a "figure-eight" wrap, one pulling in each ion (see Fig. 6).
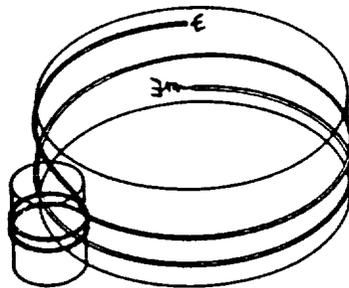

Figure 6   Roto-Lok Technology

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Gears [12]

A.   Spur Gear - Spur gears (reference Fig. 7) constitute one of the best means for transmitting motion from one shaft to another. They are usually cylindrical in shape and the teeth are straight and parallel to the axis of rotation. Mechanical energy can be transferred from one rotating shaft to another by meshing the teeth of two gears.
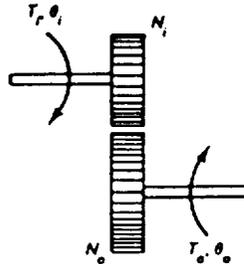
Figure 7   Spur Gears

A gear train is made up of two or more gears used to change the angular velocity, torque, force, etc, of the output relative to the input. Even though gears look ordinary their design, engineering, and manufacturing are highly developed.

B.   Squirm Drive [13, 14] - Squirm drive (Fig. 8) is a second-generation worm drive developed by Maxaxam Corp. The worm wheel carries a number of free-spinning roller spindles on its periphery. The spindles engage the roller screw thread and produce rolling motion on the point of contact between roller wheel and screw, thus reducing sliding contact friction common in conventional worm design.
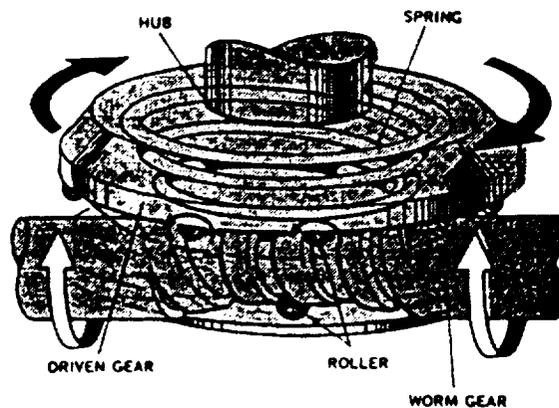
Figure 8   Squirm Drive

Torque Tubes - Torque tubes in Fig. 9 are very light drive shafts that can transmit power from one point to another. Coupled to a bevel gearset, they are used to drive wrist bend-type joints. It is possible to run several of these tubes concentrically. Oak Ridge National Laboratory uses torque tubes in their Advanced Servo Manipulator (ASM) as well as Cincinatti-Milacron in their industrial robot wrists.

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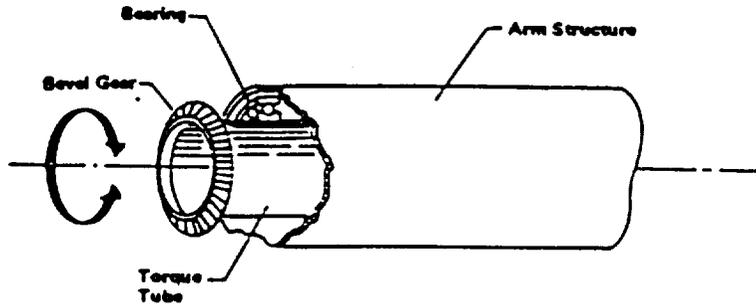
Figure 9 Torque Tubes

   Multiple Linear Actuator [15] - In this system one motor drives two
counter-rotating leadscrews (Fig. 10) in forming a mechanical "power bus".
The "power bus" can drive up to 16 linear actuators. Each actuator module
houses a pair of electromagnetic brakes and recessed inside each brake is a
freely rotating lead screw. When its brake is energized, the nut locks in
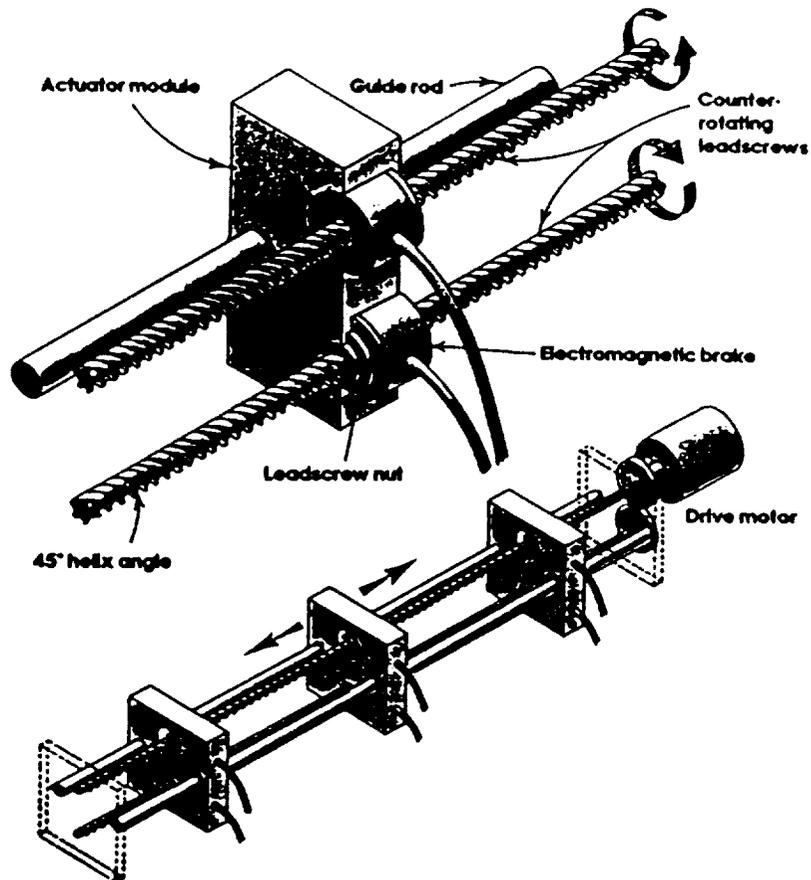
Figure 10 Multiple Linear Actuator

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place and moves the module along the lead screw. By cutting the power to the brake, it releases the nut and stops the module in a new position. Energizing the other brake moves a module in the opposite direction. The bidirectional "power bus" has been built by Victory Enterprise Technology Inc., and is incorporated in their new robotic hand.

Linkages - Linkages are often the simplest and most economical way to generate machine motion. Every mechanism can be represented by a skeleton diagram, which is the most basic representation of the specific mechanism that will produce a required motion; Fig. 11.
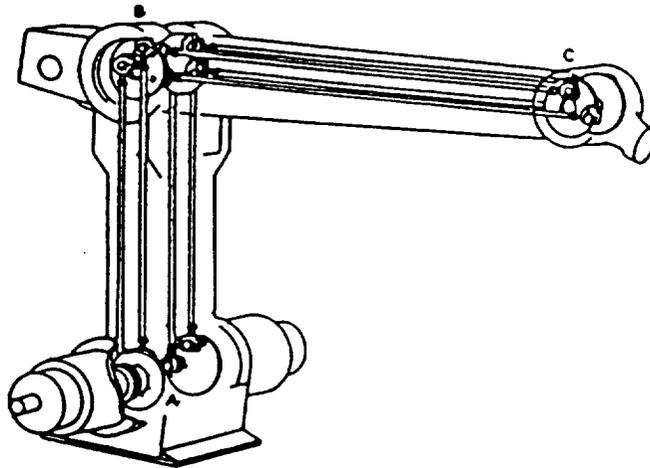
Figure 11 Linkages

Two major type of linkages are the parallelogram and the pantograph. The parallelogram can be characterized by being a compact mechanism that provides a large work envelope. The pantograph is similar to the parallelogram but is capable of magnifying its input.

Linkage mechanisms are used in the GE and Bendix industrial robots. The legs of Odex 1 by Odetics are powered by linkages as well as one of the JPL manipulators, CURV.

Speed Reducers - Speed reducers are transmissions that reduce movement and proportionately amplify torque. They perform the same functions as a gear reducer. The better known cycloidal drives are mentioned here.

Dojen Orbital Drive - The Dojen actuator (Fig. 12) consists of a housing, dual track cam, input shaft, and a output shaft. The dual track cam is sandwiched between the housing and output shaft. Each trochoidal-shaped track mates to a corresponding roller. There is one more roller than the number of lobes on each matching track. A rotary input causes the cam to orbit inside the set of rollers and phase shift occurs causing an angular displacement between each jet of rollers around the axis of the main bearing.

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Figure 12 Dojen Orbital Drive

i-Friction Drive - Figure 13 is representative of another cycloidal
The input shaft drives an eccentric that causes the inner ring to
iside the corresponding outer ring. A second inner ring, which is
ed to the primary inner ring, orbits inside a second outer ring
rigidly connected to the output shaft.
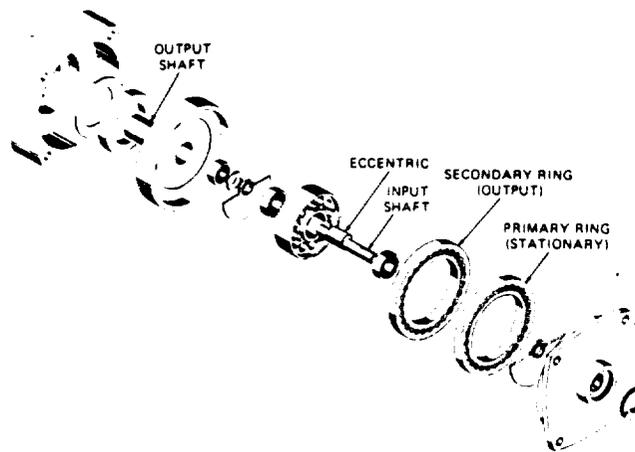
Figure 13 Anti-Friction Drive

orbiting members are designed not to mesh with the outer rollers.
, there are two more lobes in the outer ring than in the inner
Rollers separate inner and outer rings. There is one less roller
ter ring lobes. Because of the difference in the number of lobes
lers, rotation of the orbital drive produces a continuous angular
ement.

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SM-Servo-Match Precision Torque Multiplying Component - Built by Sumitomo Machinery Corp., the precision unit in Fig. 14 is used for torque multiplying. It is a planetary design and both input and output shafts are eccentric. There are only three major moving parts. The gear teeth are cycloidal shaped and are much stronger than conventional involute gears. All torque is transmitted through rollers to minimize friction and wear.
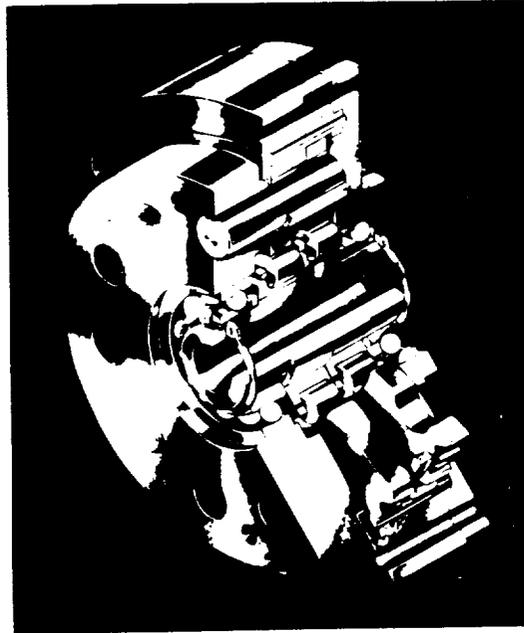
Figure 14   SM-Servo-Match Torque Multiplying Component

Actuator Transmission Criteria

In determining the optimal manipulator actuation scheme, the designer would have to approach the various choices from both the system requirement level and the component level. For example, what is the geometry of the arm? Is it a two-link manipulator or is it a gantry design? Some general decisions must be made up front and for other decisions, there might not be a choice [16].

See Fig. 15 for a systematic flow chart in determining the optimum transmission. The first fundamental question is whether the actuators be distributed or integrated? For distributed actuation, the driver of the joint is collocated at the point of flexure while integrated actuation would have the driver and point of flexure separated by some distance. Either choice will limit the type of transmission. Another major consideration is the environment in which the manipulator will operate; a battlefield scenario has distinct differences from a space environment.

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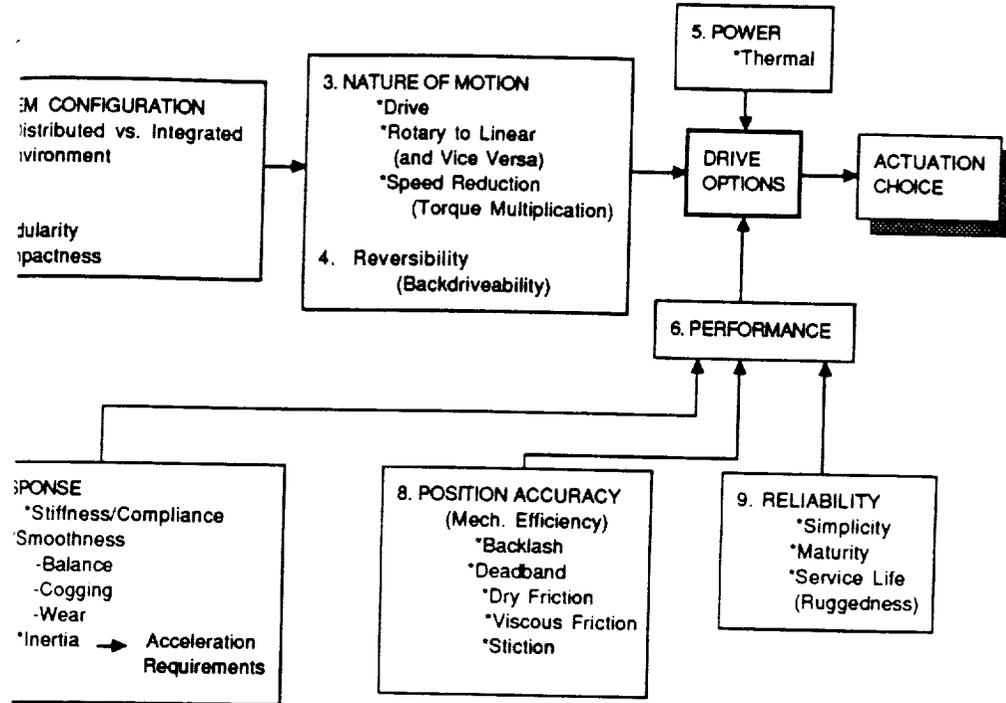
Figure 15   Transmission Criteria Flow Chart

t system requirement is the size and geometry of the arm.   Two main
his system will be the modularity issue for growth and maintenance
kaging of each particular actuator.

 case of space we have chosen a motor and need to choose the
n.   There are three primary motions for the transmission: to drive
a motion, to convert rotary to linear motion and vice versa, and to
d which consequently increases torque.   In addition, the reversi-
he transmission is a parameter.   The desirability to backdrive a
have an impact on the type of transmission chosen.   For example, a
s not backdriveable.

 point, the designer goes into more specific analysis.   The
emark was made in reference to an industrial manipulator.   "The
ransmission systems is determined by the nature of the actuators
ucture of the robot.   The choice often comes down to the question:
iculation to be moved is already set in a given position and the
osen, where can it be placed?'" [17]   Unfortunately, there is more
 the transmission than location.

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Power consumption is a key parameter for space and is primarily determined by the motor. Any inefficiencies of the transmission will directly affect power consumption. Moreover, thermal considerations are closely related to power.

The most important area for a transmission is its performance. Performance is the summation of response, position accuracy, and reliability. It is imperative that the joint respond accordingly. Compliance in the hardware will adversely affect its desired motion. Its movement should also be smooth. An unbalanced rotary motion could cause a cyclic output motion, but cogging is even worse . They lead to unnecessary wear on components. The load inertia with respect to the motor inertia will impact its acceleration requirements.

The ability to position a joint accurately is instrumental for precision tasks. The accuracy of the joint or its mechanical efficiency is characterized by not having backlash, deadband, dry friction, viscous friction and startup friction (stiction). Each nonlinearity detracts from the accuracy of the joint and should be eliminated or at least minimized.

The last performance deterrent is reliability. If the arm is inaccessible as in space, it needs to be dependable with a good service life. A mature technology is important. When designing the arm, not enough can be said about simplicity and its success in the field. Unfortunately, not everything works that way. As a result, the choice for the arms actuation scheme is a balance of system requirements with specific parameters for its performance.

Design Considerations

In comparing the various transmissions, they should be grouped by the various natures of motion. They will be divided as follows:

Drive Function--	Speed Reduction--
- Direct Drive	- Traction Drive
- Tendon	- Harmonic Drive
- Torque Tube	- Roto-Lok
- Linkage	- Gears
Rotary to Linear Motion	- Cycloidal
(vice versa)--	
- Multiple-Linear Actuator	

Drive Motion - Direct drives are reliable and have no backlash. They have low friction and low compliance. The absence of the transmission eliminates cogging and stiction that are inherent in most transmissions. However, there are a few disadvantages. The first deficiency is in its torque output. With no torque multiplication, the motor must handle all the load. It is very evident when working in 1-g. To meet its torque requirement, the motors tend to be very large and heavy. The biggest problem is that the motor will take a lot of power to operate. Secondly, its large size at each joint will take away from having a slim manipulator to reach into tight places. By not having a torque multiplier (speed reducer), the motor becomes sensitive to loads when its inertia changes.

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Linkages are an alternative to driving a joint remotely. In some cases, they can magnify torque like in a pantograph. Linkages can be extremely accurate and stiff. The positional accuracy of a link is dependent upon link flexibility, the link mode of deflection, and joint clearances. Of these factors, joint clearances are the prime source of linkage errors. Linkages are fast and reliable. The relocation of the motors closer to the base optimizes the arms weight distribution and dynamic characteristics. A parallelogram minimizes the motor inertia of the servomotor. It provides a large work envelope for a compact mechanism. Linkages are ideal for certain conditions. A major disadvantage is its limited travel and rotation. It is very difficult to get a full revolution at a pitch (rotary) joint. The output motion of the linkage can be nonlinear. The limitations on its life are a function of its bearings and connecting shafts. The stiffness of the system is dependent on the link and its material. The optimal link design may prove to be heavy or complex.

The torque tube primarily transfers power in a straight path. For the most part, they are usually used in conjunction with gears. Torque tubes are designed to minimize unnecessary weight. By doing so, its compliance increases and its dynamic response decreases. Conversely, stiffening the tube for torsion increases the weight of the tube. A major concern is the fatigue life of the tube material which is sensitive to overloading or shock loading that might twist or crack the tube. In using concentric tubes, we have found a substantial increase in weight due to the bearings.

Combining belts, bands, cable and chains under the group called "tendons" could be a misnomer. Besides the advantage of relocating the drive motors closer to the base, tendons are the simplest to use. Belts, bands, and cable perform very similarly. They are the smoothest transmissions. Its stiffness is a function of its material. They are limited by the material fatigue strength as well as the minimum pulley size. Belts, bands, and cables are not very efficient. This can be contributed to high belt tension and bearings that are highly preloaded. It is possible to have the belt skip off a pulley through wear and high speed operation. Tracking problems occur as the tendons get longer.

Chains perform like the previously mentioned tendons. They can produce a low reduction ratio by utilizing different pitch sizes of sprockets and pulleys. Chain operation is not very smooth and is more susceptible to wear and lubrication problems.

Rotary to Linear - In addition to the multiple-linear actuator system, there are several conventional mechanisms that do motion conversion. Most designers are familiar with rack and pinions and ball screws. The stiffness of rack and pinions is a function of the length of the linear motion. Without a preload there will be inaccuracies due to backlash.

Ball screws are highly efficient and offer a large mechanical advantage. They are moderately smooth with medium stiffness. Ball screws are repeatable and have high positioning accuracy. They can be preloaded or used in pairs to minimize backlash. It should be noted that an increase in preload will directly preclude an increase in friction. This is nominal for all gear-type systems. Ball screws are a very mature technology. The biggest concern with ball screws is torsional vibration and windup. The systems tend to be heavy and not always backdriveable.

On the other hand, the multiple linear actuator is a new technology that has not been proven. It can be compact and versatile. A microprocessor controls the various parameters like force, damping, and gain. The result is a delicate control system. It can reverse directions instantly by having low inertias. The motions are not backdriveable due to the high helix angle of the bidirectional bus.

With one motor actuating 16 separate joints, the elimination of individual motors reduces the weight of the system. However, conservation of energy tells us that for a limited energy source, the utilization of several joints simultaneously should reduce the performance of one or all of the joints. Secondly, each joint is travel-limited and might not fulfill the requirements. Another concern is the potential for the lead screw to bend, causing the actuator module to bind or jam.

Speed Reduction - The standard for speed reduction is a gearbox or gear technology. It is the most rugged and proven transmission. There are several factors to consider in using gears. For example, gear material, its surface treatment, manufacturing precision, gear ratios, types of gears, the gear shaft support, center distances, and lubrication all have to be considered. In particular, spur gears can be packaged compactly to obtain high ratios. They produce minimal axial forces that result in a reduced emphasis in controlling play in the gear mount. In contrast, helical gears produce axial loads that must be constrained to maintain drive stiffness. On the positive side, helical gears have a higher contact ratio which results in a smoother and quieter output. The limiting factor in the gear train stiffness is the gear tooth itself.

Gears are backdriveable. The rule of thumb is that the lower the gear ratio, the more backdriveable the drive. The majority of the backdrive resistance is imposed by the motor due to back EMF and electrical friction. There is no set ratio that designates a drive as being backdriveable. This is a good place to mention the Remote Manipulator System (RMS) on the shuttle [18]. The RMS is a distributed actuator manipulator. Each joint has a low speed and high speed gear train in series. It uses a planetary gearset for the low speed portion, while the high speed portion uses spur gears. The three wrist drives have the same gear ratio--approximately 738:1. The wrist is reportedly backdriveable as well as the shoulder, having a 1842:1 gear ratio. The RMS joints have backlash but the arm is very functional for being 50 ft long and satisfying its requirement of positioning its tip within +2 in. and +1 deg.

The next closest space manipulator is the Protoflight Manipulator Arm (PFMA) at Marshall Space Flight Center [19]. This 7-DOF arm is also a distributed actuator design. The drives were designed and built at Martin Marietta Denver Aerospace and uses a spur gear train. The drive train uses a dual path design. One motor drives two mirrored gear trains that meet at a common internal ring gear. By preloading one of the paths we were able to virtually eliminate backlash without compromising friction. The result is a joint with a high spring rate and low static breakaway friction. The gear ratios in the PFMA range from 86.4 to 110. The joint is backdriveable and is a precise positioning mechanism.

We have tested the internal ring gear output against an external drive, a standard ring and pinion. The ring gear arrangement displayed improved static and dynamic friction. It was also twice as stiff as the external drive and can be packaged more compactly.

There are other parameters to be considered besides backlash and friction. For gear trains, avoid output shaft powers greater than half the rated motor peak power. The gear train vs speed curves and the power considerations determine the various motor choices--the larger the motor, the higher the duty cycle; especially for DC servo motors. One source of friction can be attributed to magnetic effects like hysteresis drag and cogging. A high torque-to-weight ratio will result in higher magnetic friction. If weight is a major concern, gear weight is dominant for high gear ratios and motor weight dominates for low gear ratio.

The squirm drive is a notable advancement in the worm gear. Preloaded rollers that eliminate backlash and reduce friction are imbedded in the worm gear. Its rolling contact instead of sliding makes this mechanism very efficient. Stiction is reduced and the transmission is backdriveable. It is 98% efficient and has minimum backlash; however, the technology is not mature and it is not compact.

The second most common speed reducer is the harmonic drive. It is low in weight, has a high single-stage reduction ratio, is highly reliable, has negligible backlash, and has a high torque output due to the large number of teeth meshed at any one time. Harmonic drives are accurate to arc seconds and possess excellent repeatability. Gear tooth wear is negligible and the life of the transmission is as good as the surface fatigue of the bearing inner race. With no lubricant, efficiency can drop to as low as 50% from the usual 80-90% rating when using a wet lubricant.

From our earlier tests, harmonic drives 30% additional torque to overcome static friction [20]. It exhibited substantial wind-up with a nonlinear torsional spring rate at low torque. It is not the smoothest transmission and has a tendency to cog at low speed. Furthermore, the inertia of the wave genertor may be too high for certain rapid-response servosystems. The drive can have substantial spring deflection. Compliance is reduced by stiffening the system, but friction increases--and vice versa.

Using a force sensor in the drive can minimize the disadvantages mentioned previously [21]. It should be noted that JPL has harmonic drives in space on their dual drive actuator for Galileo [22].

The Roto-Lok technology is a hybrid design that combines tendon-type technology with different pitches representative of bevel gear trains [23]. As previously mentioned, a cable is extremely smooth and Roto-Lok is no exception. Backlash is eliminated by preloading the cables. This technology is mature and has been applied to precision pointing devices. The rotational stiffness of the system is maximized by locating the drive cylinder very close to the output cylinder and maximizing the contact angle of the cables with a "figure-eight" design.

Howne Roto-Lok technology has several disadvantages; primarily its limitedon and large size. The ratio of speed reduction is proportional to its r for a single stage resulting in a substantial volume. The spring increases its friction but prevents the cables from slipping; howeverriction losses are less than comparable gears and belts. The torsion-up and bending in the input cylinder is another weakness. Given tt requirements, the Roto-Lok can be very effective.

Gea are an effective load-carrying member, but also a source of backlasine pitch gear will be quieter with less backlash; unfortunately its ratcapacity will decrease. The traction drive is the result of having nite amount of teeth on a bevel gear. By preloading the tractio, the forces are transferred using the phenomenon called creep.

Zerash, high torsion stiffness, smooth operation and a compact size make thsmission desirable. The tallest pole it must hurdle is its acceptal The technology is not yet mature and needs to be developed. The amooreload required to make the transmission operational is staggeroupled with rollers that must be critically aligned, the tractior (including rolling element) is susceptible to fatigue.

Due isional slippage, a position sensor should be mounted to its motion Cor closed-loop control. The traction drive can be designed to operate :e without lubrication. Positioning accuracy can be thrown off by thermnsion. Initial tests from ongoing work at Lewis Research Center b a life of about 10 hours. The development of this transmission is :ess and the results to date are very promising.

The roup of speed reducers is cycloidal drives. They are in their early st utilization on industrial robots. They are characterized by having single stage reduction ratio, zero backlash and high torsional stiffneir small size can be coupled directly to the motor. Power is transmita rolling action, minimizing wear and frictional heat, rather than slibntact. The transmission will carry a greater load for its size due to h stronger cycloidal-shaped teeth. Its low inertia means a faster ation. However, cycloidal drives have disadvantqages. They are very heε have possible speed variations. Their efficiency drops to 50% unloadeoosed to 95% fully loaded.

Compoung

A cc joint or a differential is a clever mechanism to create a joint with con axes. These joints are ideal for a robotic wrist and possibly for the :r or a 2-DOF elbow. This is not a new device; it has been in use sinc manipulators for the nuclear industry. This compound joint can be bmpactly but not with distributed actuators. The motors could be adjacthe joint or be placed in the base.

In t: common compound joint (Fig. 16), there are two inputs with two outputs.:s 1 and 2 could be a bevel gear, a traction cone or cable driven. .nputs No. 1 and No. 2 rotate in the same direction, it results in a benon at output "A". When input No. 1 turns opposite to input No. 2, tit rolls in output "B". The differential with bevel gears can be prelo) minimize backlash. A traction input has no backlash but

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h loading. Alignment is critical and is susceptible to wear and
e same input to the differential can be accomplished with pulleys
 Precise movement can be controlled with an antagonistic pair of
With some type of tension on the cable, the same pulley can be
h a single actuator.

INPUT 1   INPUT 2
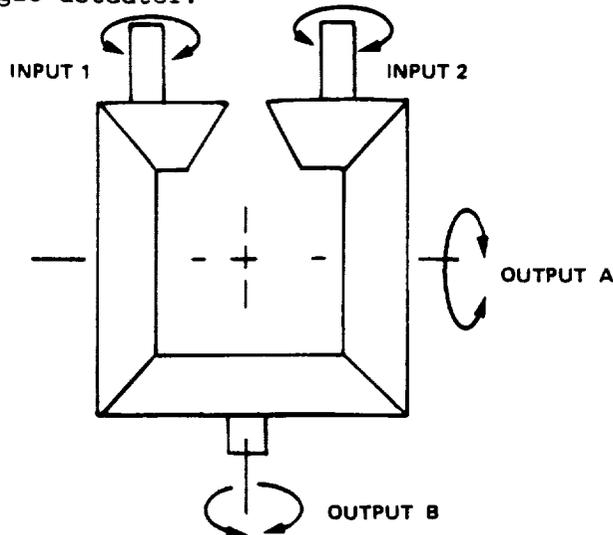
OUTPUT A

OUTPUT B

Figure 16 Compound Joint

ne physical configuration of the joint, the bend output has a
nt of travel. There is no reason a compound joint could not be
n a speed reducer. A good example is the Man-Equivalent Tele-
ot (METR) module being developed at ORNL [24]. Each motor goes
eed reducer before input to the traction differential. Finally,
 joint is more complex, but exhibits a kinematic advantage by
htersecting axes.

[

taken a look at the state of the art in robotic actuators.   In
we feel that the motor for a robotic joint in space will be a
gnet DC motor. Having settled on a motor, the options for the
e in the transmission. We have reviewed ten candidate transmis-
has its own merits as well as disadvantages. In determining the
smission for a particular joint, there is a methodology to be
hoosing the hardware. This was shown in Figure 15 and takes into
n different parameters such as performance, environment, and
e parameters were further discussed during the design consider-
also took a look at a compound joint/differential. Again, there
es and disadvantages. Finally, there is no perfect transmission.
ve their own place and application. It is up to the manipulator
ptimize his task by utilizing the desired mechanism and
to satisfy the desired requirement.

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