Cost and performance trade-offs for commercially available linear stages

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ABSTRACT

The following paper provides the practicing engineer with guidelines on the relationships between cost and various performance factors for different types of linear stages. When multiple precise motions need to be made in a system, stages are typically the solution. A number of factors should be considered before choosing a stage: cost, load capacity, travel range, repeatability, resolution, encoding accuracy, errors in motion, stiffness, stability, velocity of motion, environmental sensitivity, and additional features like over-travel protection and locking mechanisms. There are a variety of different bearing types for linear stages, each with their own advantages and disadvantages. This paper presents charts that provide relationships between the cost, travel range, angular deviation, and load capacity of various types of manual one-axis linear stages. The stages considered were those that had less than a 2.5" travel range and sold by major optomechanical vendors. The bearing types investigated were dovetail, flexure, ball bearing, double row ball bearing, crossed roller bearing, and gothic arch ball bearing. Using the charts and general guidelines provided in this paper, a more informed decision may be made when selecting a linear stage.

Keywords: stages, optomechanics, cost, bearings, linear stage

INTRODUCTION

Stages are very common system components used to provide a repeatable, precise motion in a specific degree of freedom. Any type of stage will have a several things in common: a system of constraints that allows for motion in the desired degree of freedom while constraining other degrees, an actuator that drives the stage motion (either electrically or manually), and an encoder that measures that stage motion. When choosing a stage, a variety of factors may be taken into account. Depending on the stage's application and system requirements, some factors will be of greater importance than others. This paper explores the cost and performance trade-offs between various types of manually driven, one-axis linear stages that are available from major optomechanical vendors. Linear stages are those that provide travel in X, Y, Z, or any combination thereof.

1. STAGE SPECIFICATIONS CONSIDERED

The factors taken into consideration here are cost, travel range, angular deviation, and maximum load capacity.

1.1 Travel range

Travel range is defined as the length of travel that the stage can provide. It is typically established by hard stops that mechanically prevent motion at each end. Over-travel protection is a feature sometimes provided on stages that are electronically controlled to avoid traveling beyond the range of motion. This allows the user to avoid an accidental collision of components.

1.2 Angular deviation

Angular deviation defines the maximum amount of angular motion that occurs from true linear over the entire travel range of the stage. It is defined in terms of pitch (angular deviation in x), yaw (angular deviation in y), and roll (angular deviation in z).

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1.3 **Load Capacity**

The load capacity of a stage defines the amount of static load that can be held by the stage without adversely affecting the stage motion and resolution. Larger bearings can provide larger load capacities, but result in higher friction and lower resolution. Maintaining low friction for large loads is expensive and difficult. Typically the load capacity is defined for loads in both the vertical and horizontal direction. The maximum load capacity tolerated will be when the load is centered and normal to the stage surface. Over-loading a stage can cause damage to the bearings.

2. CATEGORIES OF LINEAR STAGES

2.1 Dovetail stage

Dovetail stages have the simplest geometry, consisting of two flat surfaces sliding against each other. This provides high stability, relatively large load capacities, and large travel ranges. Due to the amount of friction from the two sliding surfaces, very precise control is difficult. They are most commonly used for coarse positioning applications.

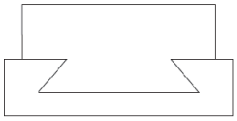

Figure 1: Cross section view of a dovetail stage

2.2 Ball bearing stages

Ball bearing stages are common for general purpose precision motions. They may consist of a single or double row of ball bearings guided by V-grooves or hardened rods. These stages have very low friction and moderate load capacity, depending on the exact ball bearing geometry used. The gothic arch style ball bearing has increased contact area over a conventional ball bearing

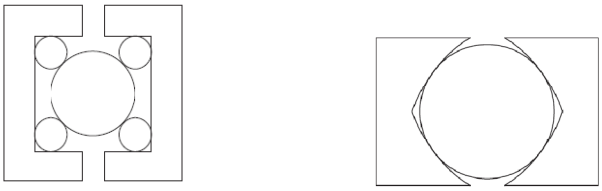

Figure 2: Cross section view of a ball bearing on 4 rods (left) and gothic arch bearing (right)

2.3 Crossed-roller bearings

Crossed-roller bearings replace ball bearings with orthogonally alternating cylindrical rollers, providing a line contact instead of a point contact. These stages offer higher stiffness, increased repeatability, and larger load capacities compared to ball bearing stages. They are also typically more expensive due to the precision fabrication required for the cylindrical rollers.

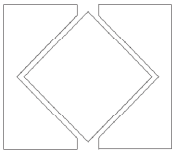

Figure 3: Cross section view of a crossed-roller bearing

2.4 Flexures

Flexures use the elastic deflection of materials due to an applied force to provide very precise adjustments. They have low hysteresis, low friction, and are good for small rotations (<~5 degrees) and translations (<~2mm) requiring very high precision (i.e fiber optics positioning). They are typically expensive, have a small travel range, and cannot tolerate large loads. Large tensile loads, however, may be tolerated in one direction based on the geometry of the flexure.

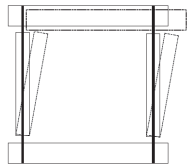

Figure 4: Example of a flexure type stage

3. COST AND PERFORMANCE CHARTS

The following charts provide relationships between the cost, travel range, maximum load capacity, and angular deviation of the types of stages discussed previously. Only stages that had a travel range of less than 2.5 inches were considered here. There are stages available with larger travel ranges than presented below. The load capacity is often provided in both the horizontal and vertical directions. For simplicity, only the maximum values were considered here. These charts are meant as an aid for the practicing engineer to make more informed decisions about what type of linear stage may be appropriate for a given application. Specific values should be verified with a given manufacturer.

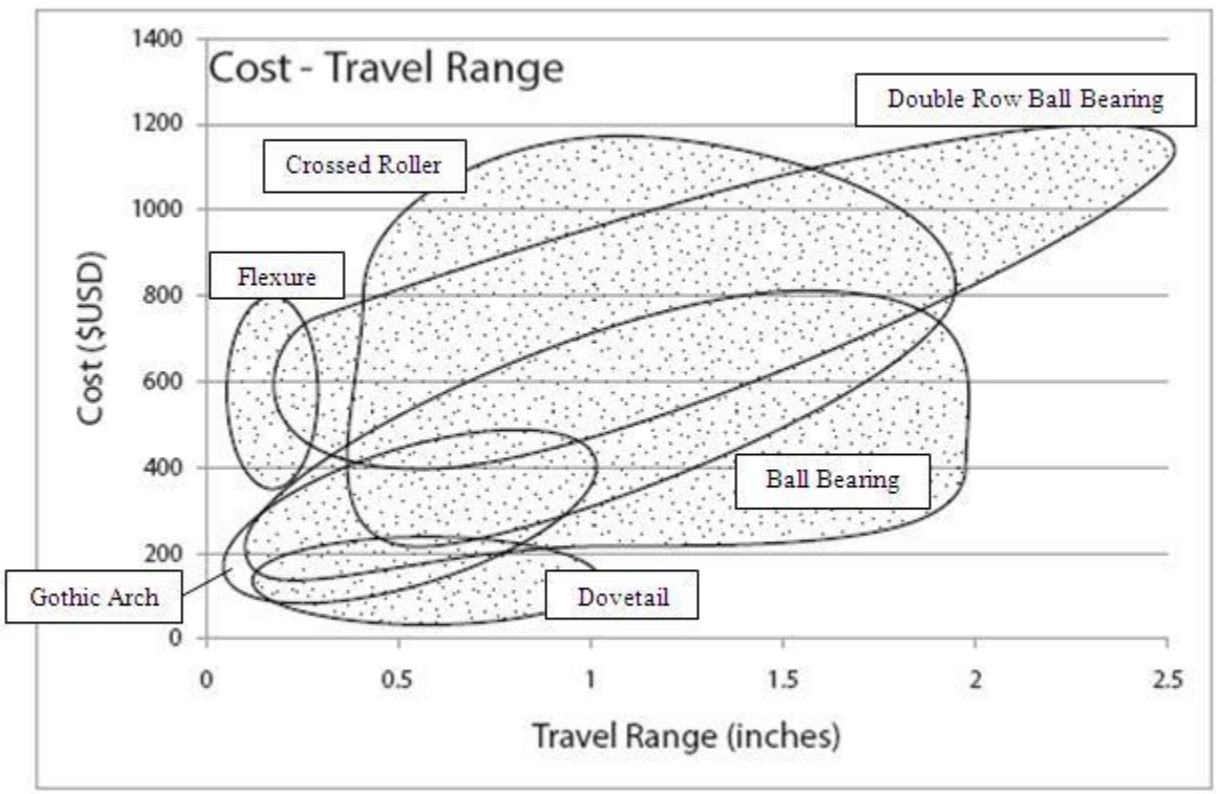

Figure 5: Cost vs Travel Range

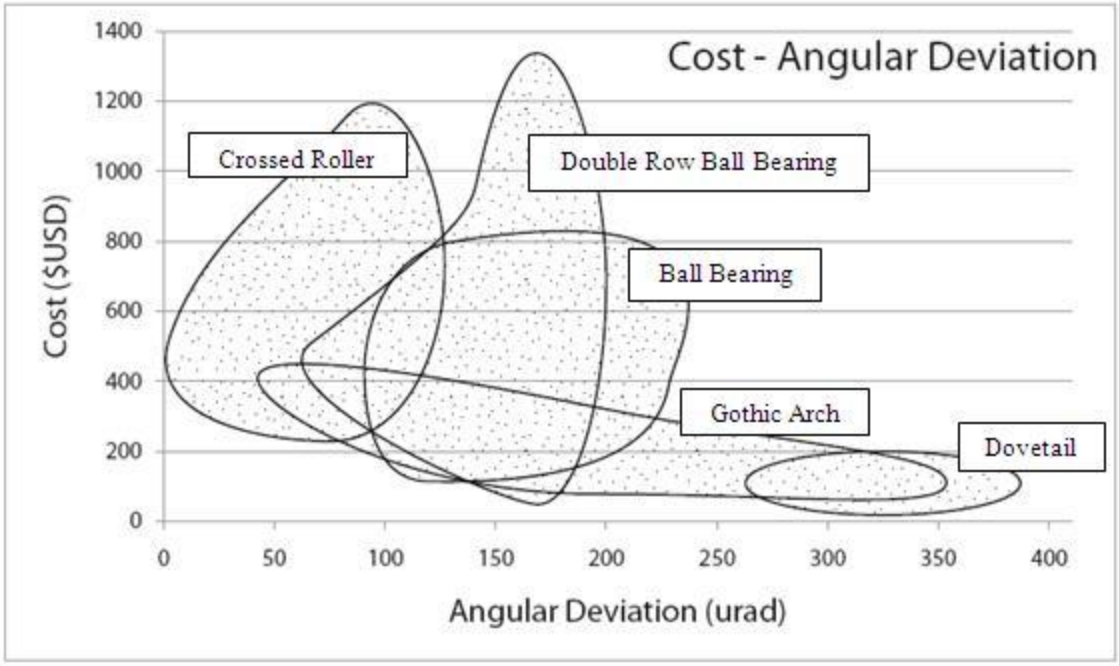

Figure 6: Cost vs Angular Deviation

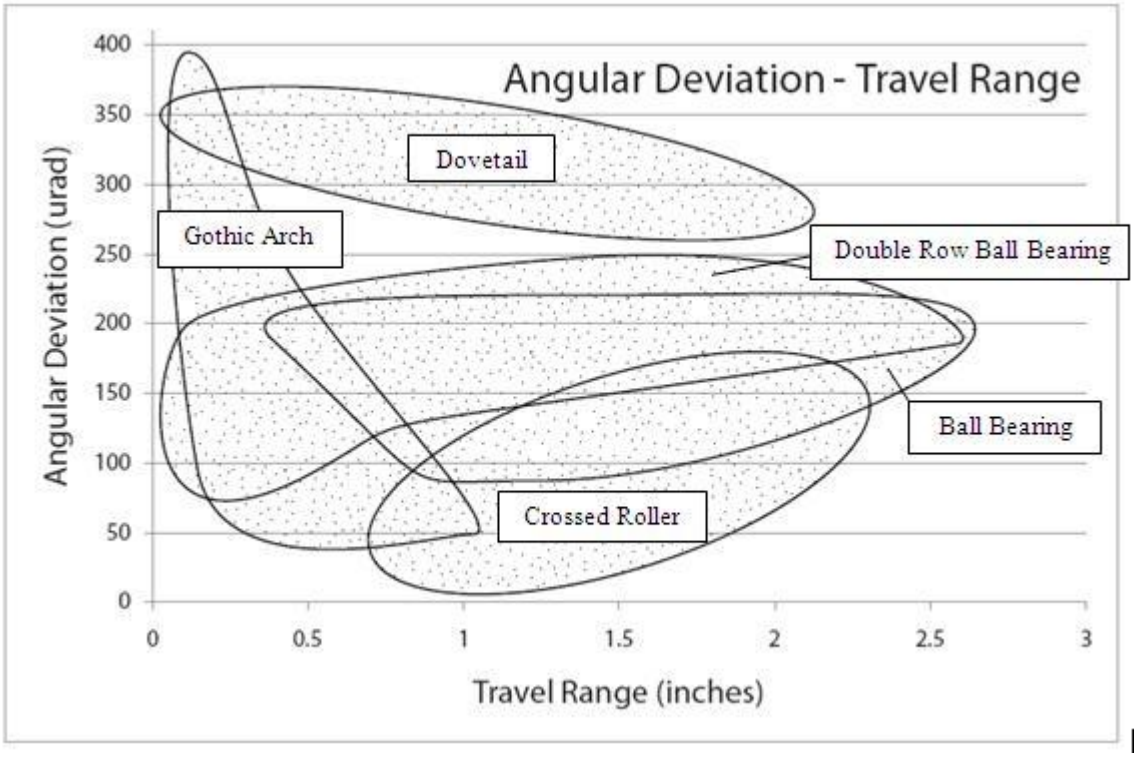

Figure 7: Angular Deviation vs Travel Range

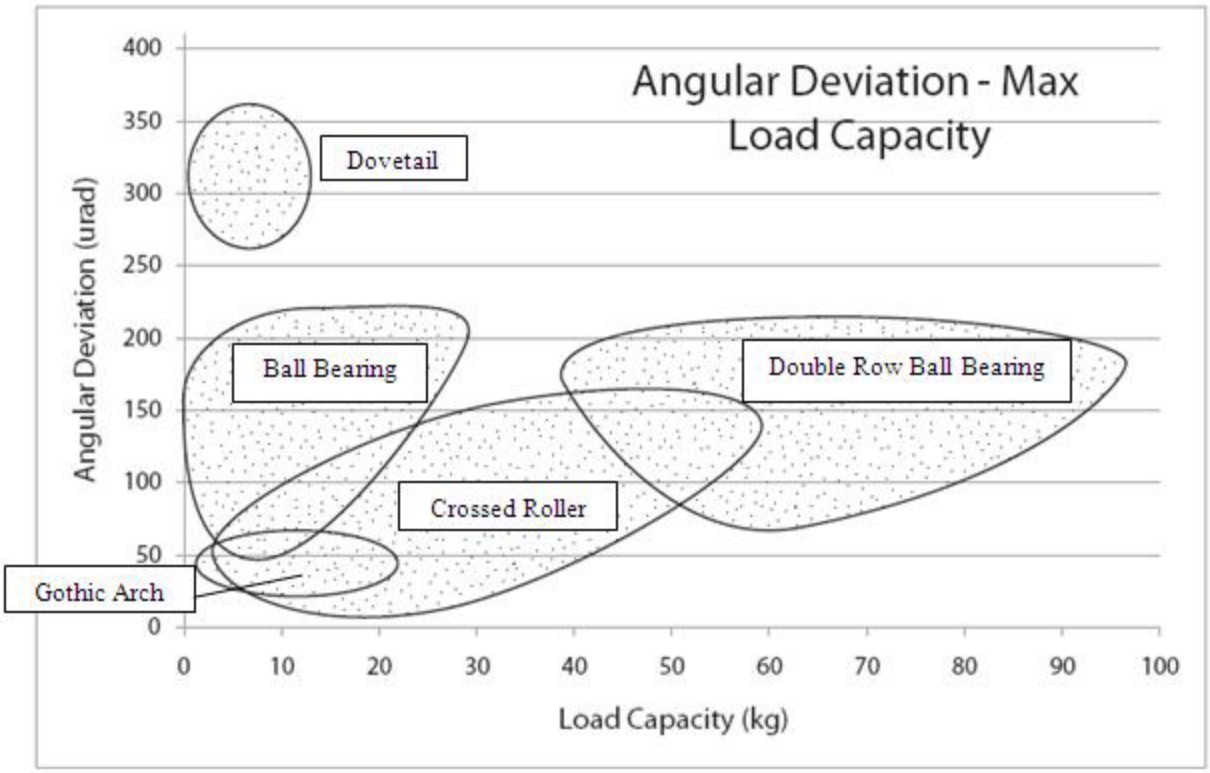

Figure 8: Angular Deviation vs Maximum Load Capacity

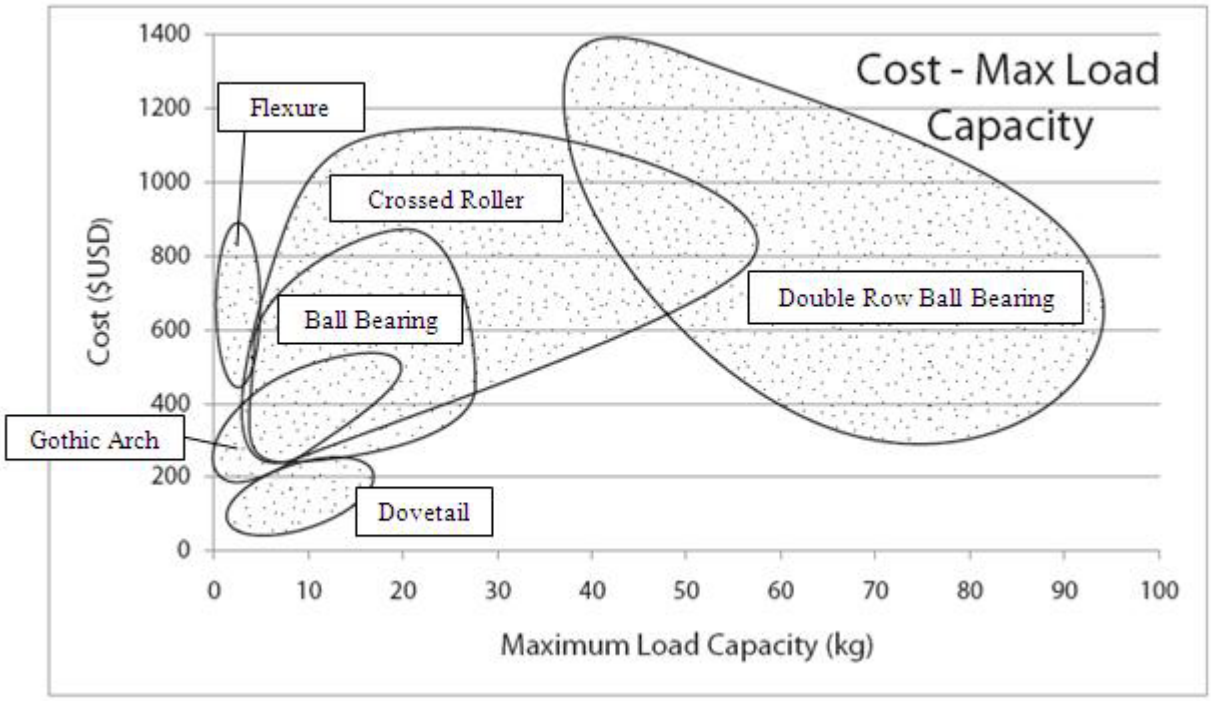

Figure 9: Cost vs Maximum Load Capacity

Table 1: Some general properties of various types of linear stages

Property	Dovetail	Ball Bearing	Gothic Arch Ball Bearing	Crossed Roller Bearing	Flexure
Cost	Low	Moderate	Moderate	High	Moderate/High
Travel Range	Large	Moderate	Moderate	Moderate	Very Small
Load Capacity	High	Moderate	Moderate	High	Low
Angular Deviation	High	Moderate	Low	Low	N/A
Stiffness	High	Low	High	High	Moderate
Resolution (um)*	~10-100	~0.5-1	~10	~1-10	Unlimited
Common Applications	Coarse positioning	General purpose precision positioning	General purpose precision positioning	Fiber optics positioning	Fiber optics positioning

*Resolution ranges provided here are approximate. Some manual stages offer resolution down to 0.1µm with the proper driver.

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