I. Background

Exlar’s founders, familiar with fluid power systems, were determined to develop an alternative actuation method - a product that would offer improved positioning performance and would eliminate the leaks that accompany pneumatic and hydraulic actuation. While extremely robust and reliable, hydraulic actuation requires significant maintenance to achieve consistent levels of positioning accuracy. Moreover, in today’s strict environmental climate, uncontrolled release of hydraulic fluid can be regarded as an environmental hazard and in some situations a fire hazard. Pneumatic actuation, due to the compressibility of air, is nearly impossible to use with accuracy or speed in electronically controlled positioning systems. Lastly, the founders wanted to develop a solution which operated above 85% efficiency rather than the 50% associated with fluid power systems.

Since electrical power is readily available and is used to create the fluid power, it seemed logical to find a solution which relied exclusively on electric power. This would eliminate the primary source of inefficiency which is the conversion of electrical power to fluid power first and then to mechanical motion. Moreover, an all electric solution would be easier to control since control systems universally depend on electric signals to monitor and control position. Thus, the high maintenance electric control valves and the inaccuracy they introduce would be eliminated.

As the search began, it was discovered that many engineers had already been replacing fluid power actuators with electric servo systems. In some low force applications even stepper systems were being employed. The results were favorable wherever the desired motion was in the form of rotation. Successful applications of electric servos included packaging, web handling, printing, winding and many others.

A major obstacle remained however when linear motion was required, particularly when one wanted to substitute an electric actuator directly for a hydraulic or pneumatic cylinder. Attempts to create electric linear motion were also observed, engineers attached servo or stepper motors to all sorts of rotary-to-linear conversion mechanisms. These devices included screw devices, belts and pulleys, racks and pinions, and cable systems and other
interesting inventions too numerous to list. The most common method observed for producing linear motion (from rotating electric motors) was the ball screw system.

This solution required the use of numerous power transmission components, belts, and couplings which all required substantial design time and careful assembly. These systems, when operating properly, were found to be fast and accurate. However, users quickly became disenfranchised because of the short life experienced in continuous duty applications and the lack of robustness to shock loads and/or contamination. And then there was the noise! Each system was designed specifically to suit the application. A standard product was hardly observed. Therefore, fluid power remained king wherever high forces, long life and robustness to harsh environments existed.

There seemed to be no existing electric counterpart with similar form factor and size and which exhibited the robustness and long life of such devices. Exlar’s founders were resolved to find a solution for this challenge. They were convinced that a market existed for an industrial grade electric linear actuator which exhibited the power density of a hydraulic cylinder and the controllability and cleanliness of a servo motor.

Knowing the shortcomings of existing solutions, the founders proceeded to identify and characterize the available technology for creating linear motion. Concluding that engineers desired an “off the shelf” product rather than a system, a list of product “requirements” was established.
II. Alternative Technologies

1. Direct Drive Linear Motors

Easily configured as a standard product, the direct drive linear motor was the first approach analyzed. To picture a linear motor, cut open a traditional brushless servo motor. Lay the magnets and armature flat and then curl the rotor back into a tube in the other direction. Now, the magnet poles are arranged parallel to the actuators output rod instead of radially around the rotor.

The stator looks like a typical stator from the outside but on the inside the phases are aligned to commutate along the length of the motor instead around the circumference. Force is produced through the interaction of the windings with the permanent magnets attached to the motor's movable output rod. Since there is no opportunity in this design to multiply the magnetic force by mechanical means (by gear reducer or lead screw) the amount of force produced is strictly limited by the strength of the magnetic fields and the amount of magnets employed.

Mechanical reduction in a conventional servo system allows a rotating motor to produce optimum power and efficiency while operating at high rotational speeds. Alternatively, it delivers high forces while operating at inefficient low speeds. In addition, mechanical reduction adds a large element of stiffness and stability to the system's operation. The combined effect of increased force, higher motor efficiency and greater stability offered by a mechanical reduction cannot be over-emphasized.

In a direct drive linear motor, we found that the current required to produce a reasonable force was considerable even if the output rod was not moving and little power was required. This relatively high current resulted in significant heat generation which limited the output power. Moreover, except in very short strokes, many magnets were needed along the stroke of the motor; therefore, the device could become very expensive. Additionally, a linear motor of this style has a larger diameter for the amount of force it is capable of producing. Thus, the solution would be considerably larger and heavier than the hydraulic cylinder it would replace.

The one major attribute of a linear motor actuator was the ability to produce very high acceleration and speed. However,
this comes at the expense of low continuous force capability and excessive heat generation and thus low efficiency. In most applications where a fluid power actuator was to be replaced, the application involved high force at low speed. Frequently, the actuator must stop and hold a force. It was this very action where we found linear motors were at their very worst.

After careful consideration, direct drive linear motors were rejected due to their low force density, awkward packaging, and inefficiency at low linear velocities. Also, we were unable to include a mechanical reduction device which would improve force density and electrical efficiency. The vast majority of applications would require the higher force density.

The founders concluded that a servo driven linear actuator needed to start with a rotary servo motor combined with some sort of mechanical rotary to linear convert with integral reduction as its foundation.

2. Force Tube Style Actuators

By the mid 90’s several companies had introduced a productized version of the ball screw system. These typically included a servo motor attached to the end of a rigid hollow case with a movable (hollow) output rod (visualize a two piece telescope.) A ball screw was fitted inside the movable tube and when turns extends and retracts the inner cylinder relative to the outer cylinder. An external servo motor was attached with coupling or belt/pulleys to the ball screw allowing the system good electronic positioning.

While force Tube actuators represent the first true product for involving an electric linear actuator, they tended to be very large compared to hydraulic cylinders. They also included troublesome couplings, belts, and pulleys. Soon users of such devices discovered that ball screws simply do not deliver the life and robustness of hydraulic cylinders.

Once again the founders went searching for a better solution.
3. The Inverted Screw Actuator

Finally, the concept of using a brushless (rotary) servomotor with a cylindrically shaped armature with an inside thread evolved. The concept was to embed a rotary-to-linear converter within the confines of the rotating armature of a conventional servo motor by turning a conventional screw configuration “inside-out”. To accomplish this, an output rod with external threads which match the internal threads of a rotating cylinder would extend or retract (if kept from turning) as the armature rotates. This design yields a very compact device and eliminates the requirements for connecting components between the servo motor and a separate rotary-to-linear converter device (or screw actuator.) The design was then termed the “inverted screw actuator” design.

Various rotary-to-linear converters with the potential for this scheme were studied. Using an ACME thread would not produce the speed or efficiency required. Next, the founders looked at incorporating a ball screw into the hollow armature. The design of conventional ball screws (those with threads on the outside of the long shaft) require that the balls coming off the end of race be re-circulated to the front of race through a tube on the outside of the follower nut. A quick analysis of the inside threaded cylinder approach showed that the balls would have to be re-circulated internally instead of externally.

This re-circulation would have required a complicated and expensive manufactured part. Also, the balls would have to make a sharp turn at the beginning and end of the race as little space is available internally. And again, the founders were reminded that ball screws simply do not provide the life and robustness that customers were seeking.
Further research unveiled a little known technology called a roller screw. The original development of this innovative device occurred in France in the early 1950’s but the expense and difficulty manufacturing limited its application. However, as the founders studied the inherent qualities of the roller screw converter, it became apparent that this compact device represented the “breakthrough solution” they were seeking.

As it turned out there were only three manufacturers of roller screws in the world, all in the industrial heart of Europe. From the beginning, it was agreed that Exlar needed to control the design and manufacture of all the primary components of its new actuator. To achieve the goal of low cost and to establish an “industry standard” for electric linear actuation, Exlar had to manufacture both the servo motor and the converter device.

Designing and then producing a roller screw proved to be no easy task. The complex interplay of all the mating surfaces of a roller screw requires an in depth understanding of the numerous and various shapes of the mating surfaces. Moreover, to achieve the promise of long life, all force transmission surfaces (over 200 in a typical roller screw) needed to make contact uniformly while under load. This required extreme precision in the manufacture of load bearing mating components. To add to the challenge, timing gears are needed to guarantee “true” roll of the rollers and to maintain synchronization of the necessary moving components.

Identifying the solution but realizing the challenge, the founders proceeded to form and refine their vision for the new company. Specific company goals were clearly set out.
III. The GS Series Development

Around 1990, Exlar was formed. Gary Shelton was hired to began researching roller screw design and developed a demonstration model of an inverted roller screw electric linear actuator.

At the same time, it was discovered that Tetrapak International was searching for an electric linear actuator device to replace their cam operated liquid carton filling machines. Tetrapak is the world's leading supplier of liquid packaging products. Evaluating ball screws in their application (one cycle per second 24/7,) Tetrapak found that these devices provided the easy implementation of electronic control they desired, however, the life expectancy did not meet the requirements of the application.

Exlar demonstrated its prototype inverted roller screw actuator to Tetrapak in 1992. Impressed by the prototype, Tetrapak immediately ordered a unit for testing and inquired if the device could last two years in their application! A prototype was delivered in December, 1992 and after only a few weeks of testing Tetrapak made the decision to incorporate “Exlar’s” in all of their new machines. With only one employee, and a couple of prototypes produced, Exlar received an order for 40 actuators with the words “Rush” stamped on it.

With the addition of Bill Zerull as president, the newly formed company began perfecting the design and developed the manufacturing processes for the Tetrapak actuators. The company committed itself to deliver their “miracle actuator” on-time and eventually to supply actuators to other companies having similar requirements. Bernie Raidt joined the company to oversee manufacturing. The first “production” units were delivered later that year.Interestingly, many of the first actuators delivered to Tetrapak are still pumping orange juice and milk today − 15 years later.

IV. Ball Screws vs. Roller Screw

Why is a Roller Screw Superior to Ball Screw?

1. Longer Travel Life

The long life and shock resistance of a roller screw (compared to a ball screw) results from the larger pressure transmission area that the roller screw design exhibits. Contact is made simultaneously at each thread on every roller. On average, 200 contact points exist in a one inch diameter, 1.50 inch long roller screw. A comparable sized ball screw will have, at most, only 50 balls in pressure contact at any time. This
characteristic of the roller screw design allows the spreading out of the forces over many contact points thus lowering the peak pressure. The spreading of the load over approximately four times the area results in a fifteen times life improvement compared to the ball screw. To explain further, the relationship of life versus load in this type of load transmission device is cubic; lowering the load by one-half results in a life of eight times. In this example, we have approximately four times the area. In practice, however, the load sharing over this additional area is very good, but not perfect; therefore, lower stress due to the larger “effective” area is a factor of about 2.5 \((4^{2/3})\) which results in a life of 15 times that of the ball screw \((2.5^3 = 15.6)\). In conclusion, the roller screw has the amazing ability of enduring even in the most arduous applications.

2. Higher Rotational Speeds

Ball screw rotational speeds have mechanical limitations. The balls being discharged from the end of the race need to return to the beginning of the race as the balls translate down the two load bearing surfaces. A sharp turn in the tube exists at both ends and the resistance of movement at these end turns impedes the balls’ movement. Moreover the balls, not being constrained in the return tube, start banging back and forth against each other. The vibration energy levels grow at an exponential rate as the rotational velocity increases which decreases efficiency and generates the loud noise associated with ball screws.
3. Greater Efficiency at High Speeds

There are significant operational differences when comparing a planetary roller screw and a ball screw. Within a ball screw, the steel balls contact each other and rotate such that mating surfaces are moving in opposite directions. Even when well lubricated, the resulting friction creates significant heat and wear as rotational speeds increase. On the other hand, the planetary rollers in a roller screw are all constrained by their journals at each end of the roller. The rollers never touch each other preventing such friction.

![Why More Efficient?](image)

There are far less limitations, in terms of speed and acceleration, on the planetary roller screw than there are on a ball screw. Roller screws can operate at rotational speeds up to 6,000 rpm which allow higher translation speed and thus higher levels of energy transfer.
4. Quieter Operation

Ball screw noise is generated by the ball colliding in the returns. The roller screw’s noise is generated from the roller timing gears which are much higher frequency (typically 10x) and does not grow exponentially with speed. As a result, roller screws are generally quieter than ball screws.

V. The GS Series Actuator

The result of Exlar’s early efforts was the development of Exlar’s GS series actuators. The inverted roller screw design brought to market an actuator which was much smaller than other commercially available force actuators. All previous actuator designs had a separate motor either mounted on the rear end or off to the side. Over time Exlar recognized that the GS actuator was valued as much for its compact size and light weight as its long life and robustness. Frequently customers asked for an even smaller size and lighter weight design, particularly when the actuators were applied on the end of a robot.
VI. The T-LAM Motor

In order to meet the demand for smaller size and lighter weight, in 1999 Exlar embarked on the development of a special purpose segmented lam motor design. The resulting T-LAM motor provided a means to increase the reliability of the actuators by maximizing the motor’s net heat dissipation capacity while at the same time reduce the actuator’s overall size.

The T-LAM design, because of its higher slot fill, minimal end turns and improved heat transmission characteristics, increased the available continuous force capabilities of the actuator by 30-50%. Exlar introduced the first T-LAM design in 2000 and by 2004 all five sizes of GS actuator were produced with T-LAM stators. Exlar’s actuators could now provide up to 50% more thrust in the same size package and operate much cooler. In addition, the T-LAM design was very flexible in manufacturing which allowed Exlar to offer a myriad of custom motor windings with little impact on delivery and cost. The T-LAM has been an important ingredient to the tremendous success of the GS actuator.

VII. Interfacing to General Purpose Servo Amplifiers

The last remaining challenge for establishing Exlar electric actuators as the “standard” of the industry was to guarantee that the company’s actuators could be matched easily and reliably with any manufacturer’s servo amplifier. Considering that today there are at least fifty known suppliers of servo this was no small task.

John Walker joined the company in 1996. Familiar with many different servo amplifier manufacturers and their variances from one to the next, John’s goal was to deliver a ‘plug and play’ actuator easily mated with whatever servo amplifier the customer specifies.
Typically, servo drives were designed to work solely with servo motors offered by the drive’s supplier. These utilized only one of the numerous types and variations of position feedback devices available. Since there was no industry standard, the task of making the Exlar actuator “universal” was daunting. John developed relationships with each amplifier supplier’s design group. Eventually, he was able to establish a process for ordering Exlar actuators with the proper feedback device and connectors. When Exlar delivered the actuator, they would properly match the servo drive being used by the customer. When a customer hooks up a GS actuator to the servo drive of their choice, he simply connects the cables which came with the drive to the factory configured actuator and updates the drive using predefined actuator operating parameters provided by Exlar. This was essential for making the GS actuator truly a standard product.

Today, Exlar’s GS Series actuators interface with all commercially available standardized amplifiers with the exception of Mitsubishi.

VIII. Exlar Today

Today the GS series inverted roller screw actuators are available in five different frame sizes and, in most models, stroke lengths up to 24 inches. Over 30,000 GS actuators have been delivered since this story’s beginning. Most of these actuators “live” for years before requiring maintenance, many in harsh environments operating 24 hours a day, seven days a week.

Moreover, Exlar’s actuators are delivering easy to use, precise positioning for applications in every field imaginable; automobile manufacturing, electronic assembly, aerospace, defense, process and valve control, turbine and engine control, medical, simulation, test, entertainment – you name it – we’re moving it.
As time progressed, requests for Exlar solutions grew which led to the development of an array of novel actuator designs. All of Exlar actuator designs employ either its roller screw technology and/or Exlar’s very high density T-LAM brushless motor technology. The revolutionary Exlar products presently offered are shown below.

EXLAR Product Line