

## **Direct Drive XYZ Positioning System with Reduced Moving Parts**

### **FIELD OF THE INVENTION**

The present invention relates to a direct drive XYZ Positioning System used for picking and placement of micro devices, such as semiconductor die, LED and optical components.

### **BACKGROUND AND DISCUSSION OF PRIOR ART**

Direct drive actuators such as linear motors have gained popularity in recent years, especially in equipment used for manufacturing electronic components and semiconductors. The commonly known advantages of using direct drive are higher acceleration, higher speed, higher accuracy, reduced moving mass, simplified design without complicated transmission systems, and better reliability without any wear and tear of moving parts associated with transmission mechanisms.

However, one advantage which is less obvious or its effects less noticed is the increased stiffness of the motion system through the use of direct drives. Driving the load directly without having transmission devices such as ball screws, belts or couplings improve the stiffness of a motion system. The effect of higher stiffness will result in shorter settling time, which is essentially an important parameter in the performance of a motion system. For example, in moving a load with a short distance of 5 mm and acceleration of 6G and within position tolerance of +/- 10 microns at the target position, if the time needed to complete the motion is 17 ms, a stiff system can have a settling time of about 1 ms, while a system that is more compliant or flexible can have a settling time of 10 ms, which is 10 times that of the stiff system. A flexible system tends to have vibrations, especially at the end of motion, where the system needs to come to a stop with a very sharp deceleration. The difference in performance between a stiff system and a flexible system can therefore be very significant, and such a vast difference in performance eventually affects the productivity of a machine in manufacturing.

Therefore, an ideal design for a direct drive system such as a linear motor system is one where the highest possible stiffness is achieved. Other than the selection of the best material (which will be limited by costs) to achieve higher stiffness, minimal parts should be used in the design, since more connecting parts means more compliance and flexibility. Related to the stiffness of a system, another important area of consideration in the design is to position the line of force to act through or be close to the center of gravity of the load mass. This will reduce the effects of moment loads caused during the high acceleration and deceleration. When the driving force and the center of mass of the load is offset by a large distance, a large moment is created and it will cause the system to bend and vibrate, thereby increasing the settling time of the desired motion.

A stiff system will be less affected by this moment load, and a flexible system with more connecting parts will be more adversely affected. The stiffness and how well the system is designed in terms of the driving force affects what we called the closed loop bandwidth of the system. Many commonly available motion controllers include algorithms and features that allow us to do a frequency response test on the system to acquire the closed loop bandwidth of the system. A system that is stiff and with the load driven near the center of gravity tends to have higher bandwidth, and the settling time for the motion of such a system tends to be shorter.

While the advantages of direct drives such as linear motors are clear and convincing, unlike a ball screw driven system or a belt drive system with pulleys, a direct drive system has one disadvantage in that it does not have any mechanical advantage as it has to drive the load directly. This limitation or characteristic of direct drive system means that the moving mass should be reduced as much as possible, so as to achieve highest dynamics as far as possible.

One of the method used in reducing the load mass is through decoupling of the actuators. "Decoupling" means separating two actuators in a configuration that will enable both actuators to work simultaneously and yet the whole weight of one actuator is not carried or supported by another actuator. Decoupling effectively does not reduce the number of actuators. It is merely a clever way of arranging the actuators and the bearings that guide the motion. Instead of mounting an entire actuator onto the moving carriage of another actuator, which will mean that the entire weight has to be supported, the effect of decoupling actuators means that only part of the weight of the actuator is carried, while the other part is mounted onto a stationary support. Many mechanisms have been developed in the past to decouple actuators.

One such prior art apparatus which decouples 3 actuators in a XYZ positioning system is US Patent 7,084,532 B2 (Widdowson et al), whose workings are shown in Fig 1. Fig 1 shows the coordinate axes of a Cartesian system marked as X,Y and Z. Three linear motors are configured to provide motion in the X,Y and Z axis. At the rear end of the apparatus is the X linear motor. The stator of X linear motor 15 is mounted to a stationary base, while the coil (not shown) moves the X table 16 (shown as a long rectangular bar) in the X direction. X table 16 is the support structure for the Y axis, connecting it to the X axis. The rails of the Y axis are mounted onto X table 16, and the runner blocks of the Y axis glide along these rails and are connected to Y table 17. Y table 17 is another connection part or support structure. It is also connected to Y linear motor coil. The Y linear motor stator 18 is fixed to a stationary stand 19. Y table 17 also supports the rails of the Z axis. Mounted on these rails are the runner blocks and Z table 20 of the Z axis. The end effector 21 and the Z motor coil are in turn connected to Z table 20. The stator of Z motor 22 is connected to the stationary stand 19.

A summary of each of the motor coils and their connecting parts and the parts they need to drive are shown in Table 1 below.

| <b>Motor coil</b> | <b>Parts to be driven/Load mass to be moved</b>                                                                                                                                                    |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| X motor coil      | X motor coil, runner blocks of X axis, table X, rails of Y axis, runner blocks of Y axis, table Y, Y motor coil, rails of Z axis, runner blocks of Z axis, table Z, end effector and Z motor coil. |
| Y motor coil      | Y motor coil, runner blocks of Y axis, table Y, rails of Z axis, runner blocks of Z axis, table Z, end effector and Z motor coil.                                                                  |
| Z motor coil      | Z motor coil, runner blocks of Z axis, table Z and end effector.                                                                                                                                   |

A summary of how the force from each motor coil is transmitted to the end effector through the next interface/connecting part are shown in Table 2 below.

| <b>Motor coil</b> | <b>Parts that transmit the desired force to the end effector</b>                                                                                           |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| X motor coil      | X motor coil -> table X -> rails of Y axis -> runner blocks of Y axis -> table Y -> rails of Z axis -> runner blocks of Z axis -> table Z -> end effector. |
| Y motor coil      | Y motor coil -> table Y -> rails of Z axis -> runner blocks of Z axis -> table Z -> end effector.                                                          |
| Z motor coil      | Z motor coil -> end effector.                                                                                                                              |

The prior art has been able to reduce the moving mass of the system, mainly by not moving the stators of each of the motors. The stators are relatively heavy due to the mass of the magnets and magnet track plates. Hence, there is a significant reduction in the mass of the moving parts. However, as we can see from Table 1, there are still many moving parts involved. Some of these parts are not insignificant in mass, such as table X, as shown in Fig 1. It is effectively a beam which needs to support the entire length of the rails of the Y axis. Moreover, with so many connecting parts, the stiffness of the system is compromised, especially when most parts are typically connected by fasteners. It can also be seen from Table 2 that the force from each motor coil also has to be transmitted through multiple connecting parts, before finally being applied on the end effector. It can be further observed that with such a decoupled design, it will be difficult to drive the force through the center of gravity of the load mass, with all the interconnecting parts and the inherent configuration and positions of the actuators.

It is desirable that a XYZ system have fewer moving parts

It is also desirable a XYZ system has its moving mass reduced as much as possible, so as to achieve highest dynamics as far as possible

It is also desirable for a XYZ system for the force from each motor coil to be transmitted more directly to the load, resulting in a system with higher stiffness, less moment loads and lower moving mass, allowing higher accelerations and shorter settling times.

### **SUMMARY OF INVENTION**

A first object of the invention is a direct drive XYZ positioning system providing motor force in the X, Y and Z axis respectively, said XYZ system comprising:

a Z axis motor to provide motor force in the Z direction; and  
a planar motor;

wherein the planar motor comprises an X voice coil motor and a Y linear brushless motor which provides motor force in the X direction and Y direction respectively, while the Z axis motor provides motor force in the Z direction.

Preferably, the X coil and Y coil of the planar motor are smaller than the magnets, fulfilling the desired stroke or travel for each axis with the following relationships:

$$S_x = L_{x1} - C_{x1}$$

$$S_y = L_{y1} - C_{y1}$$

where

$S_x$  is the maximum stroke of the X axis

$S_y$  is the maximum stroke of the Y axis

$L_{x1}$  is the distance between the edges of the two rows of magnets in the X direction

$L_{y1}$  is the distance between the edges of the two extreme magnets in the Y direction

$C_{x1}$  is the width of the X coil in the X direction

$C_{y1}$  is the length of the Y coil in the Y direction

Preferably, the X coil of the planar motor is smaller than the magnets, also fulfilling the following relationship:

$$L_{x2} - C_{x2} \geq S_y$$

where

$L_{x2}$  is the total length of each row of the X magnets

$C_{x2}$  is the length of the X coil in the Y direction

Preferably, the X coil of the planar motor is always inside the two rows of magnets, even at the extreme travel of the Y axis.

Preferably, the Y coil of the planar motor is smaller than the magnets, and must also fulfill the following relationship:

$$L_{y2} - C_{y2} \geq S_x$$

where

$L_{y2}$  is the total length of each Y magnet

$C_{y2}$  is the width of the Y coil in the X direction

Preferably, the direct drive XYZ positioning system allows the planar motor coil to be connected directly to the Z axis, thereby eliminating the support structures for X and Y, resulting in fewer moving parts.

Preferably, the direct drive XYZ positioning system has non-contact laser feedback sensors used for position feedback for both X and Y directions.

Preferably, the direct drive XYZ positioning system has a closed-loop motion controller to control the motion of the X and Y motors in both X and Y directions.

Preferably, the direct drive XYZ positioning system produces force from each motor coil which is transmitted more directly to the load, resulting in a system with higher stiffness, less moment loads and lower moving mass, allowing higher accelerations and shorter settling times.

Preferably, the direct drive XYZ positioning system allows one set of air bearings to be used to guide motion in the X and Y directions.

Alternatively, the direct drive XYZ positioning system allows linear bearings to be applied for guiding motion of the planar motor coil in the X and Y directions.

**BRIEF DESCRIPTION OF THE DRAWINGS**

For a better understanding of the invention, its advantages, and the objects attained by its use, reference should now be made to the accompanying drawings. The accompanying drawings illustrate one or more embodiments of the invention and together with the description herein, serve to explain the workings and principles of the invention.

Fig. 1 is an illustration of a XYZ system of the prior art.

Fig. 2 is a plan view of a part of the planar motor of the invention, cutting across a coil section.

Fig. 3 is a perspective view of the XYZ system of the invention.

Fig. 4 is a side view of the XYZ system of the invention.

Fig. 5 is a side view of another embodiment of the XYZ system of the invention.

**DETAILED DESCRIPTION OF INVENTION**

The present invention seeks to improve the performance of an XYZ system through the use of direct drive motors. Instead of using three separate actuators, a planar motor is used to provide motion for two of the axes, while maintaining a third actuator independently and decoupled from the planar motor. Fig 2 below shows a section plan view of the planar motor, of the invention, cutting across a coil section. The bottom magnet track plate and the magnets are shown, with the coils overlapping on top. The top magnet track plate is not shown in this illustration.

The planer motor coil comprises two sets of coils in a single plane, and assembled onto a single solid piece of material, which can be ceramic, aluminum or other suitable material. The X coil 1 comprises a single phase, and is effectively a voice coil motor. The Y coil 2 on the other hand comprises three phases, so it is effectively a three phase brushless motor. For each magnet track plate (top and bottom), two sets of magnets, 3 and 4 are assembled. The magnets 3 for the X axis comprises 2 rows, with the same polarity for each entire row, whereas the magnets 4 for the Y axis have polarity that alternates in the Y direction.

The X coil 1 and Y coil 2 are designed to be smaller than the magnets, so as to minimize coil resistance and improve motor efficiency. A person skilled in the art would observe that it is also

possible to have the coils bigger than the magnets. With the coils smaller than the magnets, and with the maximum stroke or travel for each axis determined in the design, the following relationships can be established:

$$S_x = L_{x1} - C_{x1}$$

$$S_y = L_{y1} - C_{y1}$$

where

$S_x$  is the maximum stroke of the X axis

$S_y$  is the maximum stroke of the Y axis

$L_{x1}$  is the distance between the edges of the two rows of magnets in the X direction

$L_{y1}$  is the distance between the edges of the two extreme magnets in the Y direction

$C_{x1}$  is the width of the X coil in the X direction

$C_{y1}$  is the length of the Y coil in the Y direction

It can be observed that for the X axis, even though it is the two coil portions that are longer and parallel to the Y axis that produces a desired force in the X direction, the two shorter coil portions which are parallel to the X axis will also produce forces in the Y direction. These forces are not desirable as it will affect the force (add to or subtract from) that we get from the Y coil in the Y direction. However, as long as the X coil stays within the X magnets, the force produced by one side of this coil will be cancelled by the opposing force produced by the other side of the coil. To ensure that this is the case, we need to ensure that the X coil is always inside the two rows of magnets, even at the two extreme travel of the Y axis. Hence,

$$L_{x2} - C_{x2} \geq S_y$$

where

$L_{x2}$  is the total length of each row of the X magnets

$C_{x2}$  is the length of the X coil in the Y direction

Similarly, the coil portions of the Y axis that are perpendicular to the Y axis are those portions that create the desired force when currents flow in them. The other portions that are parallel to the Y axis also create forces but are cancelled by the opposing coil portions. To prevent any undesirable forces that will affect the proper operation of the motor, we also need to ensure that

$$L_{y2} - C_{y2} \geq S_x$$

where

$L_{y2}$  is the total length of each Y magnet

$C_{y2}$  is the width of the Y coil in the X direction

It should be also be noted that the desired travel in the X and Y directions can be less than  $S_x$  and  $S_y$ , the maximum travels allowed.

Fig 3 shows a perspective view of the XYZ system of the invention. As compared to the prior art, this design is much more compact and simplified. Referring to Fig 4, which is a side view of the XYZ system of the invention, it can be seen the planar motor is placed almost at the same level as the end effect 5, with the stator 6 fixed to a stationary horizontal base. The planar motor coil 7 extends towards the end effector, and the runner blocks 8 for the Z axis are mounted directly onto a coil surface of motor coil 7 at that end. Hence, no X table or Y table (additional support structures) are used in this design. Four air bearing pads are used to guide motion in the X and Y axis. The top air bearings 9a and bottom air bearings 9b allow the coil to glide in both X and Y directions, while constraining it to move in the Z direction. This allows us to use one set of bearings for both axes of motion. Non contact laser feedback sensors are used for position feedback for both X and Y directions and a closed loop motion controller is used to control the motion. The X motor closed loop control will ensure that the coil is always within the designed travel, and the same goes for the Y motor. Hard stops which act as limits are used to prevent any over travel in case the controller fails or in the event of a power failure, although these are not indicated in the drawings. The rail 10 for the Z axis is also mounted directly onto the linear motor coil 11 of the Z axis, and this rail is guided by the runner blocks 8 mounted on the planar motor coil 7. The stator 12 for the Z axis is mounted to a stationary support.

As shown in Fig 4, CG1 indicates the center of gravity of the Z axis load (which comprises the end effector 5, rail 10 and Z motor coil 11), whereas CG2 indicates the center of gravity of the entire moving mass. The entire moving mass includes the end effector, rail 10, Z motor coil 11, runner blocks 8 and the planar motor coil 7. It can be observed that the line of action of force,  $F_z$  from the Z axis motor coil goes through CG1, which means that we are effectively driving through the center of gravity of the load mass in the Z direction. Similarly, the line of action of force  $F_x$ , from the planar motor coil in the X direction, is also driving almost at the same line where CG2 is located. For the line of action of force  $F_y$  which is located at the center of the Y coil, there is a small offset from CG2. Therefore, with this design, we are able to locate the driving force to be as close to the center of gravity of the load mass as possible.

With this configuration, not only is the moving mass reduced, the number of moving parts, especially those required for support and connection is significantly reduced.

A summary of how the force from each motor coil is transmitted to the end effector through the next interface/connecting part are shown in Table 3 below.

| Motor coil          | Parts that transmit the desired force to the end effector                                 |
|---------------------|-------------------------------------------------------------------------------------------|
| Planar motor coil X | Planar motor coil -> runner blocks of Z axis -> rail of Z axis -> Z coil -> end effector. |
| Planar motor coil Y | Planar motor coil -> runner blocks of Z axis -> rail of Z axis -> Z coil -> end effector. |
| Z motor coil        | Z motor coil -> end effector.                                                             |

With the elimination of moving support structures for X and Y, the force from each motor coil is transmitted more directly to the load, resulting in a system with higher stiffness, less moment loads and lower moving mass, allowing higher accelerations and shorter settling times.

While it is preferred to use air bearings to guide the motion in the X and Y direction, due to its simplicity and frictionless motion, it is also possible to use mechanical bearings to guide the planar motor in the X and Y directions. Fig 5 shows a side view of another embodiment of the XYZ system using mechanical bearings. In Fig 5, the planar motor coil 7 is supported by two sets of linear bearings, 13 for guidance in the X direction, and 14 for guidance in the Y direction. With this embodiment, there will not be any significant change in the center of gravity of the moving load, and the planar motor coil is still driving the Z axis load directly as described in the previous preferred embodiment.

It should be noted that the arrangement of the planar motor and the Z motor are examples of the present invention. Other conceivable combinations are possible, such as placing the planar motor in a vertical plane and having the third axis perpendicular to the planar motor, to provide XYZ motion in a different manner. It is understood that such variations or modifications fall within the *spirit and scope of the above description*.

#### **ADVANTAGEOUS EFFECTS OF THE INVENTION**

Unlike conventional XYZ positioning systems, regardless of whether the axes are coupled or decoupled, using a planar motor to replace for two of the actuators simplifies the design, making it more compact. The costs of making a planar motor is also lower than making two separate actuators, with less material needed. The reduction of connecting parts also reduces the effort in manufacturing and assembly. Stacking errors due to machining errors and alignment errors

during assembly are also reduced. The planar motor can be assembled easily as the two coils are made on one solid piece.

It is also possible to use air bearings for guiding the motion of these two axes, thereby simplifying the design further. Only one set of air bearings is needed for both axes and a very compact design can be achieved.

Since both coils of the planar motor are embedded on one piece of solid material, with the planar motor, the tables or support structures that are typically used to connect a motor coil to another motor coil or other moving parts can be eliminated. This reduces the number of parts required, thereby reducing the moving mass as well. With a reduction in mass, higher accelerations can be achieved with the same amount of motor force, which translates to better performance.

More importantly, with the reduction of connecting parts, the stiffness of the entire motion system is improved. With higher stiffness, higher accelerations can be achieved, with short settling time after the end of motion.

Moreover, with the planar motor design, the motor forces are acting very close to the center of gravity of the entire load mass. This reduces moment loads during high acceleration and deceleration, which can cause vibrations. Hence, having the motor force driving close to the center of gravity gives better dynamic performance.

**CLAIMS:**

1. A direct drive XYZ positioning system providing motor force in the X, Y and Z axis respectively, said XYZ system comprising:

a Z axis motor to provide motor force in the Z direction; and  
a planar motor;

characterized in that the planar motor comprises an X voice coil motor and a Y linear brushless motor which provides motor force in the X direction and Y direction respectively.

2. The X coil and Y coil of the planar motor as claimed in Claim 1, wherein said coils are smaller than the magnets, fulfilling the desired stroke or travel for each axis with the following relationships:

$$S_x = L_{x1} - C_{x1}$$

$$S_y = L_{y1} - C_{y1}$$

where

$S_x$  is the maximum stroke of the X axis

$S_y$  is the maximum stroke of the Y axis

$L_{x1}$  is the distance between the edges of the two rows of magnets in the X direction

$L_{y1}$  is the distance between the edges of the two extreme magnets in the Y direction

$C_{x1}$  is the width of the X coil in the X direction

$C_{y1}$  is the length of the Y coil in the Y direction

3. The X coil of the planar motor as claimed in Claim 1, said coil is designed to be smaller than the magnets, also fulfilling the following relationship:

$$L_{x2} - C_{x2} \geq S_y$$

where

$L_{x2}$  is the total length of each row of the X magnets

$C_{x2}$  is the length of the X coil in the Y direction

4. The X coil of the planar motor as claimed in Claim 3 wherein the X coil is always inside the two rows of magnets, even at the extreme travel of the Y axis.

5. The Y coil of the planar motor as claimed in Claim 1, said coil is designed to be smaller than the magnets, must also fulfill the following relationship:

$$L_{y2} - C_{y2} \geq S_x$$

where

$L_{y2}$  is the total length of each Y magnet

$C_{y2}$  is the width of the Y coil in the X direction

6. A direct drive XYZ positioning system as claimed in Claim 1 that allows the planar motor coil to be connected directly to the Z axis, thereby eliminating the support structures for X and Y, resulting in fewer moving parts.

7. A direct drive XYZ positioning system as claimed in Claim 1 wherein non-contact laser feedback sensors are used for position feedback for both X and Y directions.

8. A direct drive XYZ positioning system as claimed in Claim 1 wherein a closed-loop motion controller is used to control the motion of the X and Y motors in both X and Y directions.

9. A direct drive XYZ positioning system as claimed in any of the preceding Claims wherein the force from each motor coil is transmitted more directly to the load, resulting in a system with higher stiffness, less moment loads and lower moving mass, allowing higher accelerations and shorter settling times.

10. A direct drive XYZ positioning system as claimed in Claim 1 that allows one set of air bearings to be used to guide motion in the X and Y directions.

11. A direct drive XYZ positioning system as claimed in Claim 1 that also allows linear bearings to be applied for guiding motion of the planar motor coil in the X and Y directions.