Force Control Basics

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Introduction

Force control is a technology that has developed to fill a void in the automated manufacturing process. In many manufacturing processes parts are brought to a net dimensional shape by machining, casting, forging, or molding. These parts often meet the dimensional specifications, but still require additional processing to achieve a desired surface finish. In the case of machining operations, residual marks and scallops are removed from the part. Other processes, such as injection molding, casting, and forging, require the removal of flashing, gates, and parting lines. These blending and finishing operations are applications where switching to a force controlled process rather than a dimension driven position controlled manufacturing process is required.

Blending of parting lines or removal of cutter mismatch, scallops and flashing requires a human touch. This human touch is a form of compliance and is a property that rigid, position based machine tools do not have. Compliance in the context of automated surface finishing is the ability to compensate for mismatch between a tool and a part surface, and is based on maintaining contact rather than position. The primary consideration when contacting a part surface is controlling the amount of force being applied by the tool. In automated surface finishing the tool is often an abrasive media and the amount of force applied directly affects the Material Removal Rate (MRR). The MRR is the amount of material in volume removed in a specific time. It is important to note that in most applications the abrasive media moves with the compliance.

In general, to successfully implement an automated surface finishing system some type of compliance and force control is needed. There are two commercially accepted methods of force control used in automated surface finishing today. The first method, "through-the-arm" force control, applies force using the position of all the robot axes in unison. The second method, "around-the-arm" force control, uses the robot for positioning motion only, and applies a controlled force through an auxiliary compliant end-of-arm tool. This paper will discuss the theory, applicability, and features of each of these two technologies.

Through-the-arm Force Control

Through-the-arm force control has been called the "Elegant Solution" since it appears to be such a simple and natural extension of robot control technology. The appeal of through-the-arm force control results from the compelling urge to draw an analogy between robots and human beings. If a human can apply a force and move a tool over a part, then why not use a robot to move a tool over the same part. A human being has a brain; a robot has a computer controller. A human being has muscles, arms and hands to grasp tools; a robot has servo motors, a manipulator and a gripper. It seems obvious that if a robot were given a sense of touch with some type of force transducer then the machine should be able to apply forces just like a human. While this analogy seems viable there are subtleties which make through-the-arm force control difficult to successfully implement.

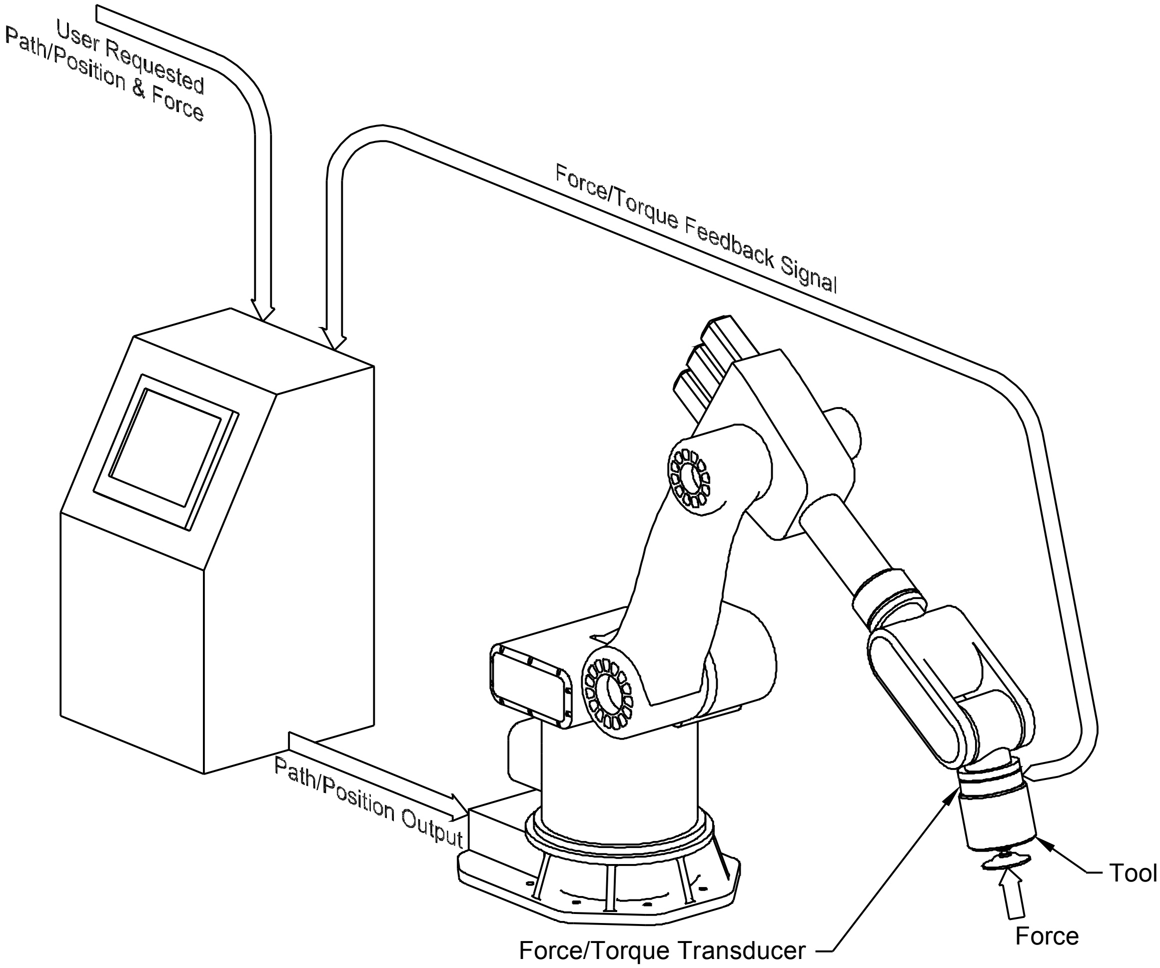


Figure 1. Through-the-arm force control

Through-the arm force control is accomplished by mounting a six-axis force/torque transducer to the robot wrist plate and then attaching a tool to the transducer as shown in Figure 1. To apply a given force, the robot pushes the tool against the part surface and a force/torque transducer outputs a corresponding electronic signal. This output signal indicates the magnitude of the forces along the X, Y and Z axes and their associated torques about those axes relative to the robot wrist plate. The robot controller receives the force/torque transducer output signal and compares it to the user-requested force to determine if a force error exists. Invariably some force error will exist and the robot arm must change position relative to the part surface to apply more or less force. This compensating motion brings the force error to zero and maintains the user requested force. A complication exists in that any force correcting motion must also be performed in conjunction with the user prescribed path over the part during processing. This means that, by using the force/torque transducer feedback to position the robot arm during motion, the transducer and the robot are acting together, becoming a coupled system.

Through-the-arm force control has been shown to work best with highly compliant media and/or compliant backup pads. Compliant media reduces the sensitivity to positional errors. The compliance of most robots is low, which means they have a moderate stiffness (i.e., compared to a machine tool). The robot can not be designed to be too flexible or compliant, because the arm requires a certain stiffness to achieve the necessary positional accuracy. With a stiff manipulator the media/backup pad must provide the mechanism for bridging any positional inconsistencies.

The limitations of through-the-arm force control are most apparent when a stiff non-compliant media or backup pad is used. The position of the media relative to the part surface then becomes much more critical since the stiffness of the overall system has increased. For example, if the stiffness of the robot and media is assumed to be k = 500 lb./in. then a part to media mismatch of just 0.010 inch results in a force variation of 5 lb., which could be enough to stall the motor or gouge the part.

Part to media mismatch during processing is caused by the robot arm not being able to physically respond quickly enough to eliminate the force error. Using stiff media with through-the-arm force control, exceeds the physical response limits of the manipulator. Regardless of how fast the robot controller processor speed is, the robot arm has some mass and the motors some limited torque. This statement implies that there is some finite acceleration rate, or response, which the arm is capable of achieving. In surface finishing applications if the robot is moving across a part surface with some nominal velocity and encounters a sudden rise on the surface of the part, the robot must correct the position *instantaneously* to avoid a force spike. An instantaneous position response is all but impossible, since it would require an infinite acceleration of the robot arm.

The effects of force spikes on the part surface can be minimized and a satisfactory surface finish achieved if the velocity of the tool across the part is decreased. The path velocity must be slowed so that the robot's servomotors can respond in a timely manner and maintain the desired force. Therefore through-the-arm force control is most useful in low speed applications with very compliant media and relatively flat parts. In processing applications that produce very fine, airborne contamination, through-the-arm force control has a distinct advantage in that the force-torque sensor can be easily shielded from the environment.

Around-the-arm Force Control

Around-the-arm force control is a method that is based on using the robot arm for positioning and motion only. This method de-couples the force control from the robot controller and servomotors. Around-the-arm force control can be applied to floor-mounted equipment or mounted a robot as end-of-arm tooling. The robot mounted force control device, shown in Figure 2, is an auxiliary tool that adds an additional axis of motion to the system. This axis of motion provides the compliance that is needed for automated surface finishing. Compliance is extremely important in compensating for part location mismatch or unexpected additional material. The axis of motion and compliance can be either linear or rotary. The linear stroke is usually around 1 inch (25 mm) and the rotary motion is typically 5 degrees. Greater compliant strokes are possible, but not normally used since the robot can easily position the tool within these limits.

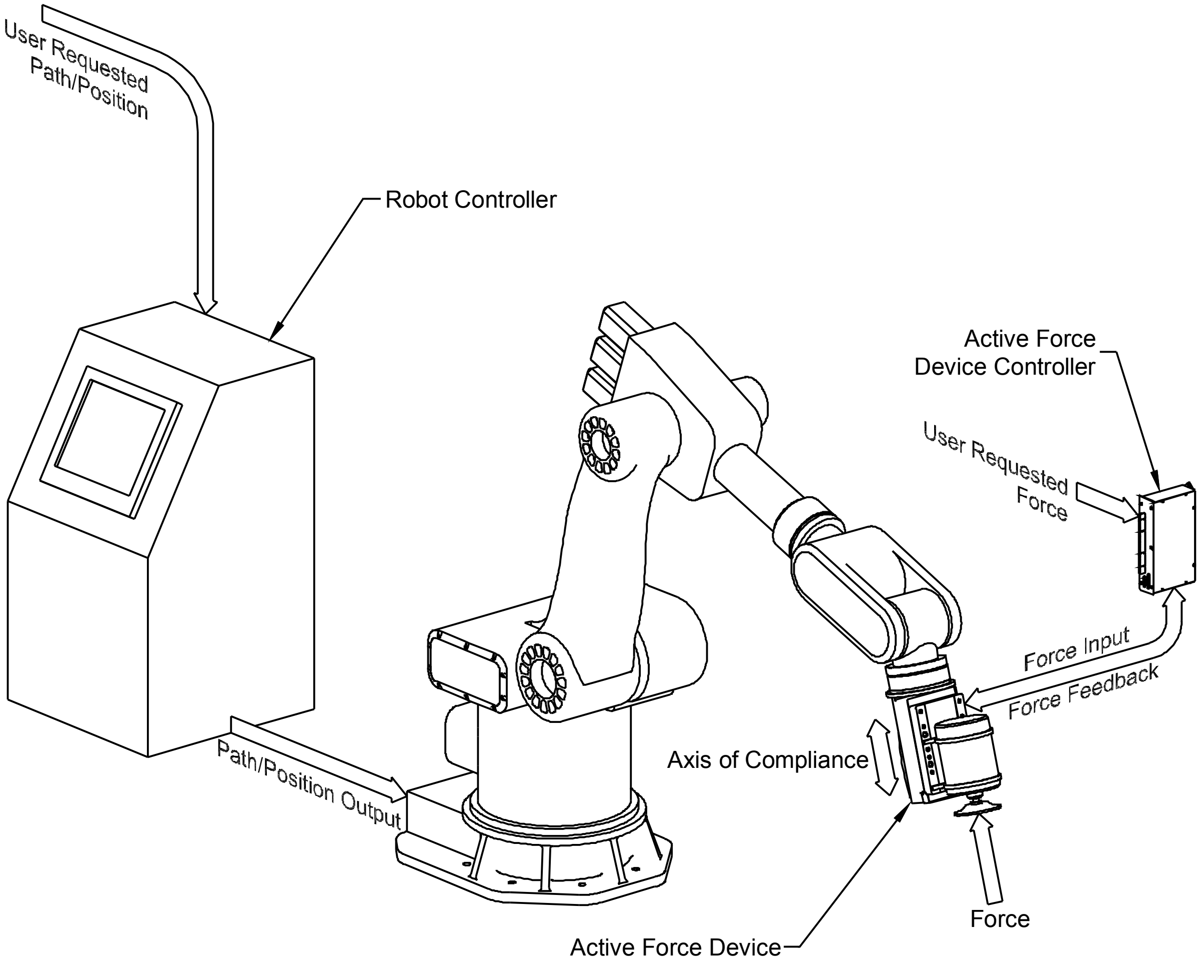


Figure 2. Around-the-arm force control

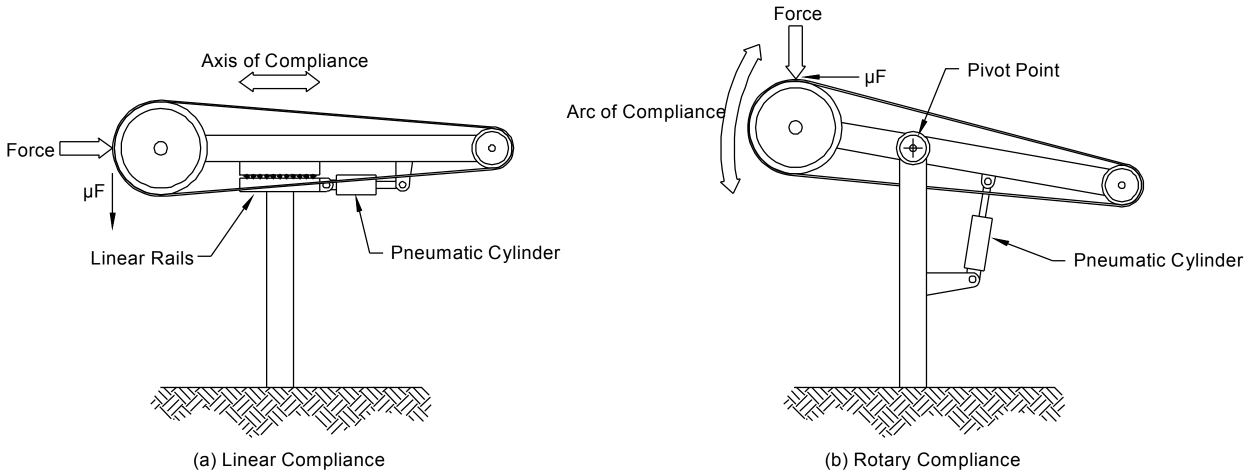
In order to maintain a force and compensate for position errors along the axis of motion and compliance, the force device must have some means of actuation. Many techniques have been tried with the earliest force tool designs using a spring to provide a force along the axis of motion and compliance. This technique is simple and inexpensive, but not very accurate or flexible. Hydraulic actuation can provide a high force to size ratio, but is inherently stiff and does not have the natural compliance needed for surface finishing. A servomotor coupled with a lead screw has also been used to actuate force devices, but this method is similar to using the robot with its servomotors and gearboxes -- no compliance. Another option is electromagnetic actuation (i.e., voice coil). The electromagnetic actuator has the necessary compliance with the additional bonus of zero operating friction, but the high weight to force ratio, and saturation problems after extended periods of operation have hampered the implementation.

The actuation method of choice for current commercially available force control devices is pneumatics. A low weight to force ratio and excellent natural compliance due to the compressibility of air makes pneumatics an obvious choice. Additional benefits include the low cost and availability of compressed air. With either linear or rotary compliant motion, and pneumatic actuation, around-the-arm force control techniques provide process flexibility. This flexibility allows the robot to carry the media to the part using compliant tooling or the part to the stationary media using floor-mount compliant tools.

Generally in surface finishing if the robot carries the tool it is call an end-effector or end-of-arm tool (EOAT) and if the tool is stationary it is referred to as a floor-mount tool. In almost every application, whether using a compliant robot tool or a stationary floor-mount tool, the abrasive media will be carried by the compliant tool. And, in either case, the part will be rigidly held either by a floor-mounted fixture or a robot gripper. It is important to remember that the force due to gravity can have a significant impact on the compliant tooling and must be compensated for, especially if a robot wrist-mounted compliant tool is used.

Floor-mount Compliant Tools

When a floor-mounted compliant tool is used for surface finishing, it is rigidly mounted and remains stationary in the robot workspace during part processing. This means that any gravitational effects along the axis of motion remain constant and can be easily compensated for. Robot compliant EOAT, on the other hand, can have the axis of motion moved into any orientation by the robot arm and require some means to compensate for the changing gravitational and inertial effects.



(a) Linear Compliance

(b) Rotary Compliance

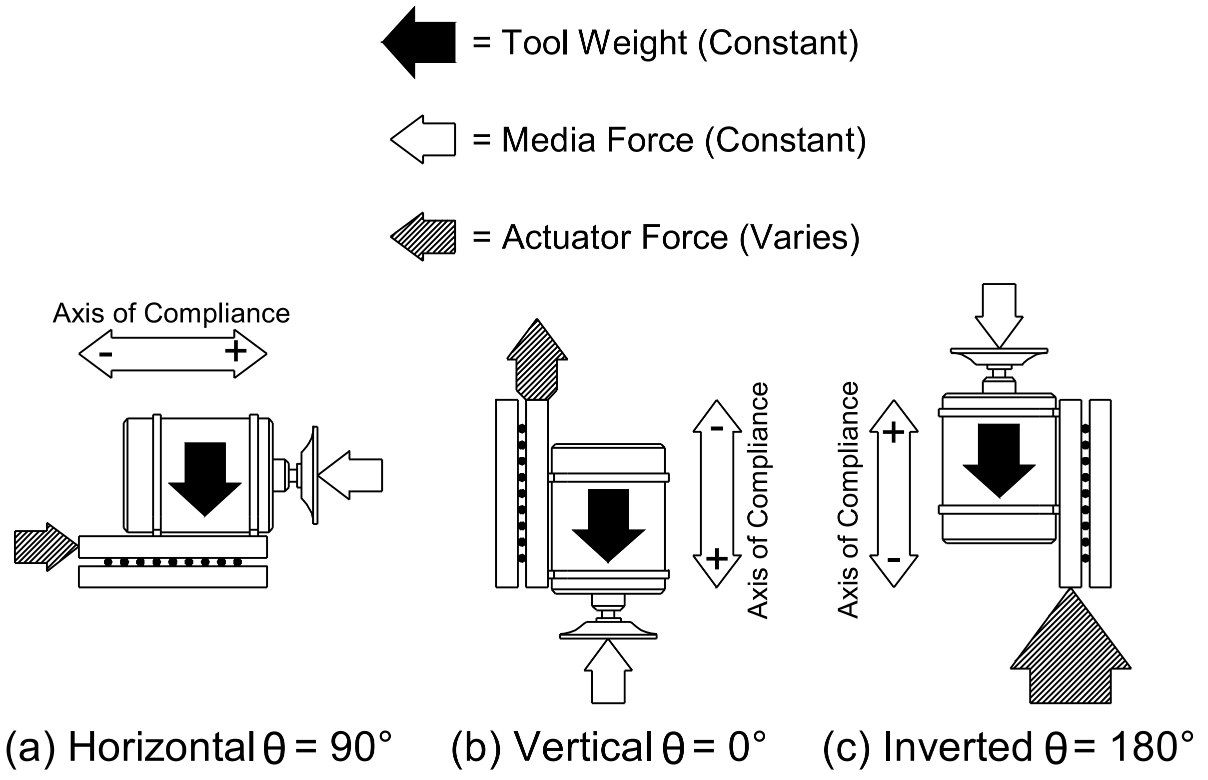
Figure 3. Axes of compliance

A floor-mount compliant tool with a linear axis of motion is shown in Figure 3a. The tooling (i.e., brackets, motor, and media) is attached to a carriage that rides on linear rails. To apply a force the carriage is directly connected to a pneumatic actuator. As the part is moved into the media the carriage will move along the axis of compliance. The media will push against the part with the requested force throughout the entire linear stroke. A floor-mount compliant tool can also have a rotational axis of motion as shown in Figure 3b. The part is brought to the media in a direction that causes rotation around the pivot point. As the floor-mount compliant tool rotates through the arc of compliance a constant force is provided by the pneumatic actuator and applied to the part surface. The media will push against the part with the requested force throughout the entire rotation.

Robot Wrist-mount Compliant Tools

Mounting the force control device to the robot wrist requires special consideration due to the changing orientation of the axis of compliance. The Laws of Physics require that the force of gravity acting on a mass be always in the vertical direction downward (i.e., pointed toward the center of the earth). This means that the weight of the tooling, media, and carriage will always act in the same vertical direction downward. The carriage axis of compliance or motion on the other hand will probably not remain in one orientation, but will continuously change as the robot arm moves it through space.

Figure 4 shows the effect of changing the orientation of the end-effector. The actuator force must change magnitude and/or direction to maintain a constant force on the media. As shown in the diagram, the relative size of the arrows indicates the magnitude of the force the actuator must apply to compensate for the force of gravity as the tool rotates. The carriage axis of motion is in the horizontal orientation and the tooling weight is pointing in the vertical direction downward in Figure 4a. In this orientation the tooling weight does not have any effect along the axis of carriage motion. The pneumatic actuator force applied to the carriage is in the positive direction and equals the opposite required media force.



(a) Horizontal θ = 90° (b) Vertical θ = 0° (c) Inverted θ = 180°

Figure 4. The effect of changing orientation on the actuator force

In Figure 4b the force device has been placed in the vertical orientation with the media pointed downward. It should be clear that the tooling weight is acting in the vertical direction downward toward the positive carriage axis of motion. In this orientation the tool weight is acting along the axis of compliance opposite to the media force. The actuator force is now in the negative direction, opposite to that illustrated in Figure 4a. In fact, the pneumatic actuator force must counteract some of the tool weight since the media force is less than the weight of the tool.

In Figure 4c. the force device has been changed to the inverted orientation. The tool weight is acting in the vertical direction downward, but is now pointed in the direction of negative carriage axis compliance. With the required media force and the tool weight added together and acting in the same negative direction along the carriage axis of compliance, the actuator force must be increased significantly to counteract the tool weight and media force.

The examples illustrated in Figure 4 demonstrate that the changing orientation of the compliant EOAT is much more complicated than a floor-mount compliant tool. The floor-mount compliant tool only requires tool weight compensation if a non-horizontal axis of compliance is selected. In this situation the tool weight compensation force will remain constant and can be easily taken into account during the initial development and will not require subsequent adjustment.

Types of Force Control

There are two methods used to implement pneumatic force control: passive and active. Passive force control is an open loop control system with no means to adjust for force errors. Active force control is a closed loop control system that can automatically adjust to reduce force errors. A practical example will help to illustrate the difference between open loop and closed loop systems.

The state of Texas takes great pride in the fact that it is the largest of the 48 contiguous United States. Being such a large state, ranchers spent a great deal of time on the road in their pickup trucks. In the days before electronics, whenever Bubba, a typical West Texas rancher, wanted cruise control on his pickup truck, he would prop a long stick between the dashboard and the accelerator pedal. Bubba would watch the speedometer and slowly adjust the stick until the desired speed was achieved. This open loop system worked well on the flat west Texas desert, but difficulties arose when he encountered the Davis Mountains. The vehicle speed would slow while climbing a mountain and increase when the vehicle started down the other side. These fluctuations above and below the speed limit were undesirable given that a Texas Ranger could be over the next hill.

When electronic cruise control became possible, it was time to get rid of the stick. Now the accelerator pedal position could be set based on the current speedometer reading of the vehicle as compared to the driver’s chosen speed. When the driver’s chosen speed and the speedometer reading differed, the accelerator position automatically increases or decreases to compensate. Automatically moving the accelerator position means that the vehicle will maintain a constant speed in flat or hilly conditions without driver intervention. Adjusting the throttle position based on velocity sensor (speedometer) feedback make this an active, closed loop, system.

In pneumatic passive force control devices, the setting of air regulators to specific pressures is analogous to using a stick to hold the accelerator pedal. To provide a constant force the regulators are set to pressures that will result in the desired force. The pressures in the actuator can be adjusted to compensate for gravity effects, but there is no way to determine the actual force being applied by the device during processing. So, as the force device moves across the part surface, changing in orientation, the carriage moves in and out and the force being applied varies. This is similar to ascending and descending a hill in the cruise control example. Without a speedometer or a force transducer the actual speed or force is never really known. Not accurately knowing how fast you are going, or in the case of automated surface finishing, what force you are applying can cause problems. Having no velocity feedback in the pickup truck makes this a passive, open-loop, system.

PASSIVE MECHANICALLY COUNTERBALANCED FORCE DEVICES

The first type of device to be discussed is the mechanically counterbalanced unit shown in Figure 5. The most notable feature of this configuration is the use of a mass to physically counteract or balance the tool weight. The counterweight eliminates the need to determine the orientation of the device as the robot moves it around. After the tooling is mounted to the carriage, metal plates are added or removed from the counterweight until the device is balanced. No matter what orientation the device is placed in the two masses will counteract each other. A pneumatic actuator can be then be used to supply the additional media force. No other external input is necessary for this unit to compensate for gravity in various orientations.

One disadvantage of the counter weight method is that if the payload on the carriage changes, then the counterweight must be manually reconfigured to balance the force device. This is a problem when tooling weight changes as the media wears or if different types of media are used for a multi-step process. If the unit is not re-balanced a force error equal to the weight differential will result as the device changes orientation.

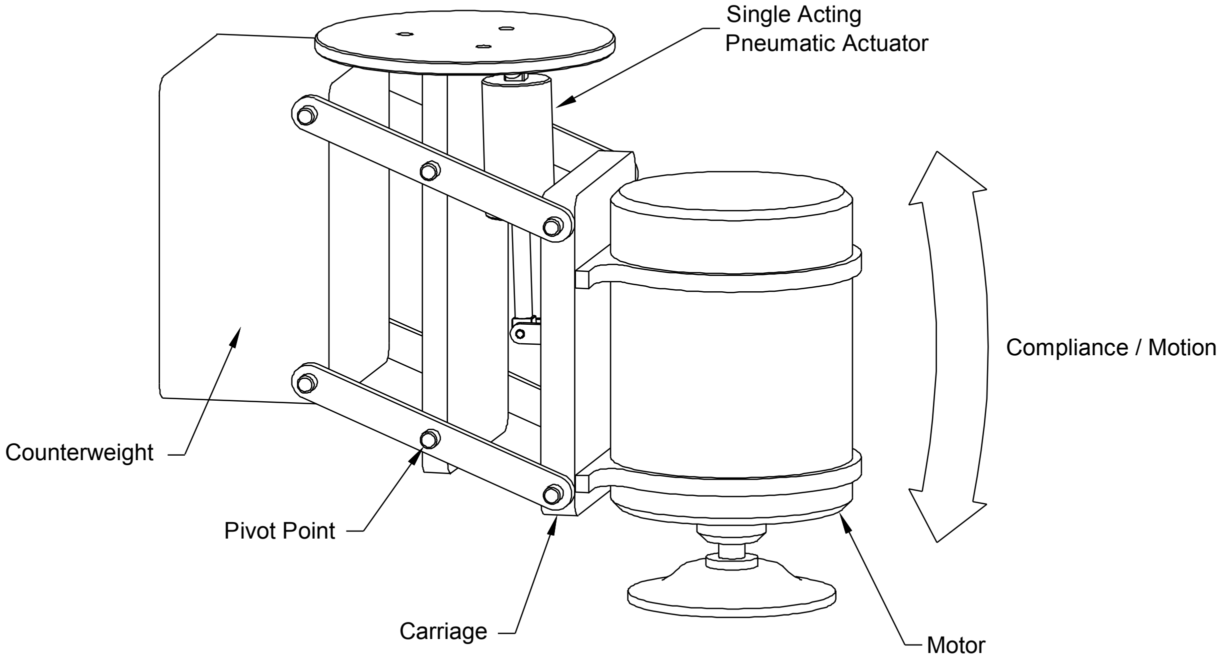


Figure 5. Mechanically counterbalanced passive force device

Another potential problem with mechanically counterbalanced force devices is oscillation or "hopping" on the part surface when low forces are required. This is caused by the device being a simple second order mechanical system with a lot of mass, an abrasive media that behaves very much like a stiff spring, and a low damping coefficient. The low damping coefficient is a result of the low friction requirement that is placed on all force devices. Any friction in the compliant motion and actuator will result in a force that offsets the desired media force. When low process force levels are used the forces associated with the inertia of the device (i.e., motor and counterweight) can be large and oscillation will occur. Generally as the process force increases the tendency to oscillate will decrease. Media "hopping" across the part surface usually results in a less than satisfactory finish. Mechanically counterbalanced force devices are rarely used any more due to the availability of more stable and configurable air counterbalanced devices.

PASSIVE AIR COUNTERBALANCED FORCE DEVICE

The passive air counterbalanced force device differs from the mechanically counterbalanced device by not requiring a counterweight to offset the tool weight. Adjusting the air pressure on each side of a pneumatic actuator can compensate for the tool weight. When the passive air counterbalanced tool is to be moved in any orientation by the robot a double acting actuator is required to offset the tool weight. But, if the unit is operated in only one orientation, then it may be possible to use a single acting actuator. Figure 6 illustrates a simplified air counterbalanced design.

Three methods can be used to determine the amount of pressure required in the actuator to provide the necessary counterbalancing and the required force output. The first method assumes that the EOAT will remain in the same orientation relative to gravity during part processing. If this is the case then the pressures in the actuator will remain constant throughout the process. To set the pressures in the actuator some type of force measurement system (i.e., a load cell, calibrated weight) is attached to the device. Using the measurement system the regulators are set to produce the required force. The pressure regulators can be manually adjustable with this method, which means that no electrical signals are required. Manually setting the regulators is a very simple solution, but one that provides very little process flexibility.

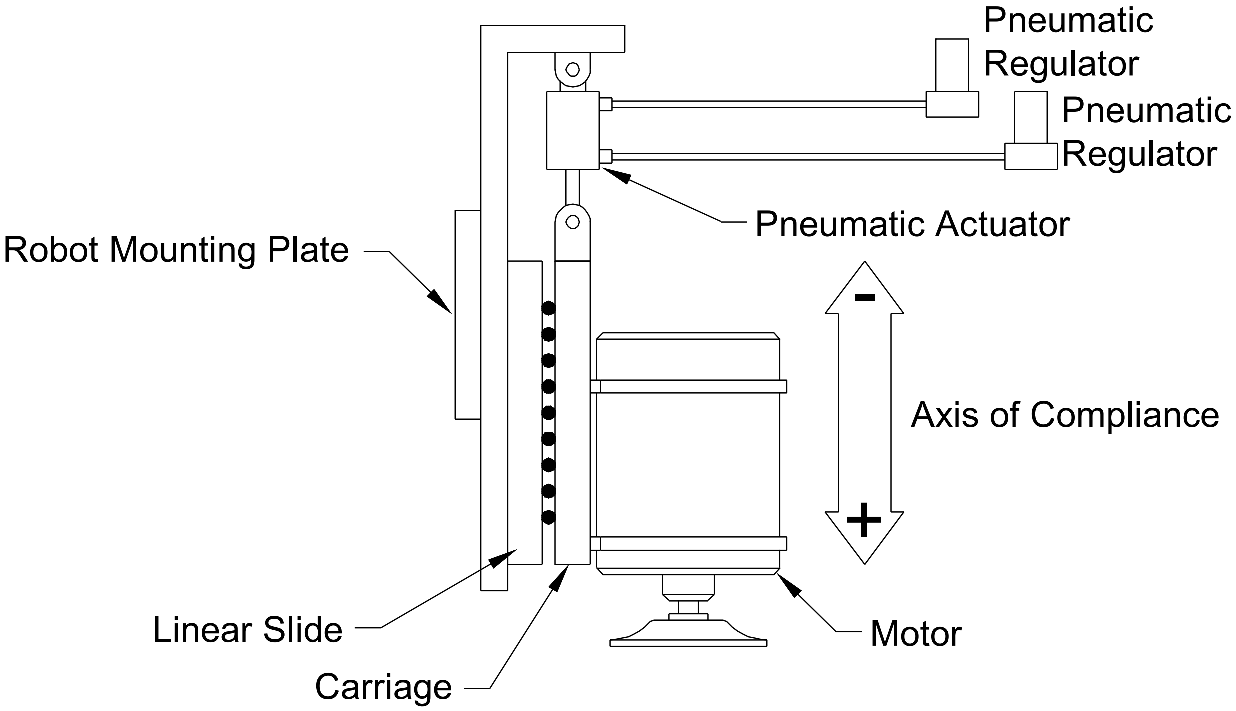


Figure 6. Air counterbalanced passive force device

The second method for setting the pressure regulators is necessary if the device will not be in a constant orientation. As the orientation changes the pressures in the actuator must change to counterbalance the weight and maintain the desired media force. When the robot path for a part is taught, the regulator pressures are also set for each path point and saved in the robot controller by the user. This typically requires the use of some type of electronically adjustable pressure regulators that are interfaced to the robot controller. This method can become quite tedious since each time a new path point is taught, a force measurement must be taken to determine the settings for the pressure regulators.

During part processing the pressure regulators will receive new signals from the robot controller each time it comes to a taught path point. This means that the accuracy of the force device is directly related to the amount of points that the user decides to teach. If the programmed part path causes the orientation to change gradually then the accuracy of this method may be sufficient. For parts with rapidly changing orientations the force accuracy probably will not be acceptable for demanding processes. Therefore this method is generally best suited for simple parts with relatively flat features.

The third method will work with either a constant or changing orientation and involves a set of equations that continuously run on the robot controller to adjust the regulator pressures. The equations have the following general form:

$$P_p = \frac{F_w\,(1 - \mathrm{Cos}(\theta_g)) + 2F_a}{2A_p}$$

$$P_s = \frac{F_w\,(1 + \mathrm{Cos}(\theta_g))}{2A_s}$$

Where:

P_p = Primary side (rodless side) actuator pressure

P_s = Secondary side (rod side) actuator pressure

F_w = Tool weight

F_a = Media force

A_p = Area of primary side (rodless side) actuator piston

A_s = Area of secondary side (rod side) actuator piston

θ_g = Carriage angle relative to gravity

The equations listed above usually reside in the robot controller and must be programmed by the manufacturer or user. Several robot manufacturers have software packages available that include these calculations and a teach pendant user interface. In order to calculate the required pressures and generate the corresponding pressure regulator signals all of the variables and constants in the equations must be determined. The surface areas of the pneumatic actuator are constants and can be easily obtained from the manufacturer. The weight of the tool is a value that can be constant or vary depending on the process. The tool weight includes the mounting brackets, media, motor and carriage. The total weight of all these components must be determined manually from some type of force measurement device like a load cell. Any tool weight measurement inaccuracy will transfer directly to the device output causing a force-offset error.

As shown in Figure 4, the orientation of the device clearly affects the magnitude of the tool weight along the carriage axis of compliance and must be compensated for. Determining the orientation of the robot wrist plate in real time is not an easy task. One technique is to physically measure the angle and save the values along with the robot path points. This can be a time consuming procedure and as discussed earlier there is an accuracy problem associated with only using a limited number of points. A second technique uses the robot controller to calculate the angle of orientation. The robot controller calculates the angle of orientation by monitoring the location of each of the joints on the robot arm in real time. The calculation speed of the angle of orientation by the robot controller has a direct effect on the accuracy of the force device. The calculated value of the angle of orientation must be supplied to the passive equations for the pressure signal calculations.

The final variable needed for the pressure signal calculations is the user requested media force. The user requested media force can be changed at any point during part processing. The user is responsible for determining this value and must input it into the robot controller. Determining the correct media force and all the other process variables is probably the most difficult task of the automated surface finishing installation. With all of the constants and variables available the robot controller calculates the pressure settings for each side of the pneumatic actuator.

The passive air counterbalanced force devices do have some disadvantages. The open loop control scheme does not directly monitor the force being applied to the surface, rather the pressure regulators try to maintain a constant pressure. Maintaining constant pressures is not the same as maintaining a constant force, so this limits their accuracy. These traits relegate passive force control devices to performing lower speed operations on relatively flat parts with loose process requirements. Implementing air counterbalanced passive tools also requires additional time and integration skills to interface with the robot controller.

ACTIVE FORCE CONTROL DEVICES

The final method to be discussed is active force control, which is an outgrowth of the passive air counterbalanced method. Active force control differs from passive force control by utilizing a stand-alone controller to manage a closed-loop system that continuously monitors the applied force and corrects for any errors. The active technology is based on directly reading the force applied by a double acting pneumatic actuator. This guarantees a much more accurate system than passive systems that apply the media force based on pressure regulation.

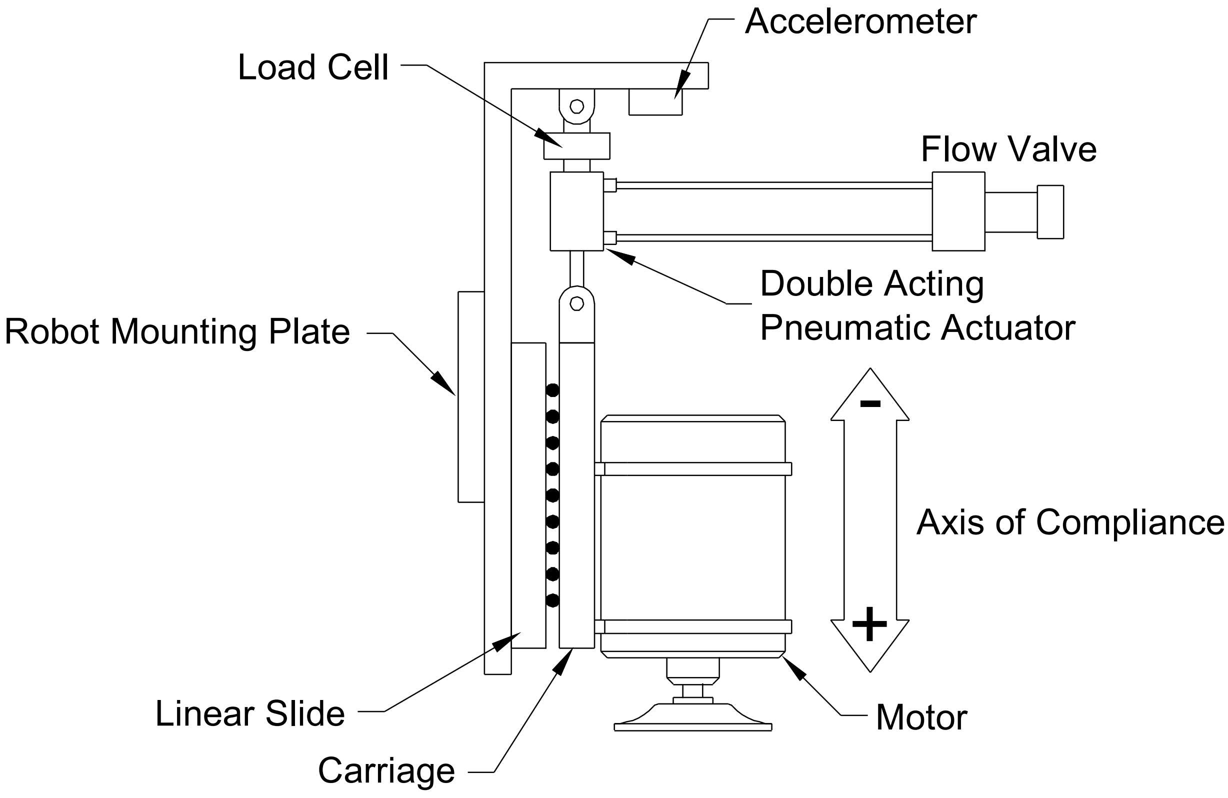


Figure 7. Active force device

Active force control for automated surface finishing is a technology that was developed in 1990 at the University of Texas at Arlington. The fundamental difference between the passive and active methods is the placing of a load cell (i.e., force transducer) in series with the pneumatic actuator to provide a direct force reading. This novel approach to force control was patented in 1995 by the University (U.S. Patent No. 5,448,146). The load cell connected in series with the pneumatic actuator as shown in Figure 7, allows a external dedicated controller to continuously monitor the force being applied by the actuator. An additional advantage of series attachment of the load cell is that any friction in the pneumatic actuator is included in the force output signal, thereby compensating for it.

Getting back to the cruise control example, knowing the actual force on the actuator is analogus to knowing the speed of the vehicle displayed on the speedometer. Just as Bubba must know the actual speed of the vehicle to maintain the desired speed, the force device must know the actual force applied by the pneumatic actuator to maintain a desired force. The difference between the desired speed and the actual speed of the vehicle yields a velocity error, just as the difference between the user requested media force and the actual load cell force yields a force error.

To correct for the vehicle velocity error, the accelerator is automatically depressed or released, likewise to correct for the force error, pressure on one side of the pneumatic actuator is automatically increased while the other is decreased. Under active control the flow valve does not attempt to maintain a constant pressure, but instead adjusts flow into or out of each side of the pneumatic actuator to drive the measured force error to zero. Closed loop control causes the pressures in the pneumatic actuator to change very quickly based on the force error signal. The active tool controller rapidly positions the flow valve to correct the force error and achieve the desired media force. The net result is that the active unit provides a very accurate processing force.

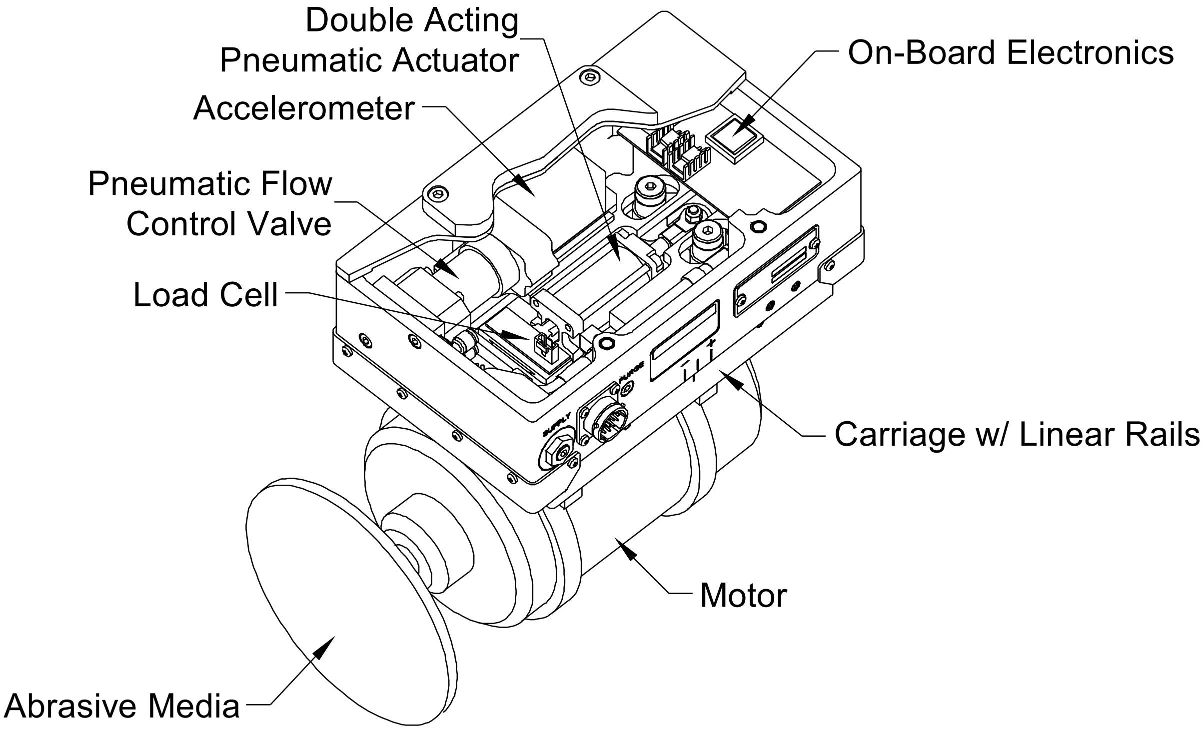


Figure 8. Active Force Tool

The active device must also compensate for tool weight gravitational effects like the passive air counterbalanced device. However, unlike the passive device, the active device carries a single axis accelerometer. The accelerometer, shown in Figure 8, measures the orientation angle along the carriage axis of compliance using the effect of gravity. Directly measuring the force device orientation eliminates the need to acquire joint angle information from the robot controller. The accelerometer also provides a continuous output signal that is not dependent on the update speed of the robot controller. This means that the accelerometer signal can be read every millisecond or faster, resulting in a more constant media force over contoured surfaces.

Another important advantage of mounting the accelerometer in the force device is the direct reading of inertial effects induced by moving over the part. Inertia effects become significant when a force device is moved in a curved path with the axis of rotation being some distance from the carriage and in the same plane as the carriage axis of motion. If this occurs the tool weight is subject to centripetal forces that tend to push the media toward or away from the part surface. The onboard accelerometer senses the increased or decreased acceleration in conjunction with the gravitational effect and the active controller quickly varies the flow to the pneumatic actuator to maintain the user requested force on the part.

Alternatively, the passive air counterbalanced device requires the user to manually weigh the tooling. Besides being inconvenient, the weight of the tool can change during part processing. A grinding wheel is an example of abrasive media that changes mass significantly with wear. The active device solves the tool-weighing problem by using the load cell located inside the force device. Weighing the tool (including the motor, media, and carriage) is accomplished by placing the active device carriage in approximately a vertical position so that the axis of motion is reasonably aligned downward. The active controller sends signals to the force device to suspend the carriage at mid stroke. At this point the tool weight is supported entirely by the load cell and the active controller can easily read its weight. The weight value is stored for later use in the control algorithms.

The active force device relies on a stand-alone controller that takes the user requested force and automatically delivers that force to the part with a high degree of accuracy. The stand-alone controller also allows additional processing features. In the simplest applications, where the force remains constant throughout the process, a user can input the value directly into the active controller and operate the robot completely separately. If the processing of the part requires different force levels at different points in the robot path, then the active controller must be connected to the robot controller. The user can select force values at different points in the robot program and then send the force signal to the active controller based on the path location on the part.

Summary

This paper has given a brief introduction to the basic principles of force control for automated surface finishing operations. Force control techniques allow automated equipment to efficiently perform operations that are cost prohibitive or require a level of consistency not possible using manual methods. When deciding on force control processes there are a number of technologies available to choose from. Through-the-arm verses around-the-arm, end-of-arm devices verses stationary backstands, active force control verses passive. Choosing the most appropriate force control technology for an application is one of the first steps to guaranteeing a successful surface finishing process. The matrix listed below should help with comparing the different methods and allow you to choose the best one for your processing needs.

	Cost	Setup	Contamination	Overload capacity	Accuracy	Robot dependant
Passive Around-the-arm	Lowt	Mid	Mid	High	Low	No
Active Around-the-arm	Mid	Low	Mid	High	High	No
Active Through-the-arm	High	High	Low	Mid	Mid	Yes