Programming with Force Control

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Introduction

As the number of robotic applications and installations continues to grow the need for effective and efficient robot programming techniques grows proportionally. Currently almost all robotic programming is accomplished through teach-by-show techniques. While these techniques are tried and true, they are tedious and time-consuming and are becoming more and more of a burden in today's dynamic manufacturing environment.

Off-line simulation and lead-through programming promise acceleration and streamlining of the robot programming process. They enable a user to program robot motions in a simulated "virtual" computer environment leaving the robot to continue in production. These simulated motions are compiled and downloaded to the robot controller where they can be fine-tuned in a very short time to provide optimal performance.

Robotic surface finishing applications are a particular challenge to current programming techniques -- both teach-by-show and off-line simulation. Automated surface finishing applications require both fluid motion profiles as well as a delicate touch. Given enough time, programming techniques mentioned above can generate fluid motions. The delicate or human touch is provided through various forms of compliance.

This paper discusses some of the factors which should be considered when programming surface finishing applications. The discussion will begin with basic surface finishing equipment configurations, followed by a section on path programming considerations, and finally a section on compliance.

Basic Configurations

Robotic surface finishing applications usually fall into one of two broad categories. *Part in Hand*, or *Tool in Hand*. As the names suggest, *Part in Hand* applications are those in which the robot brings a part to be finished to a fixed surface finishing apparatus. *Tool in Hand* applications reverse the situation in that the robot applies a surface finishing tool to a fixed part.

Part in Hand

Part in Hand applications are most often used where the part to be finished is relatively small in size. Gripper tooling allows the robot to pick up the part and manipulate it against the abrasive finishing media. *Part in Hand* systems are common in manufacturing because of several benefits in their use.

One benefit is that often robot load/unload operations can be combined with the surface finishing operation at a single work station, i.e., a robot can remove a part from a serial line conveyor, finish the part, and then place the part in final packaging or intermediate holding matrices for painting, etc. Doubling up these operations can provide a much greater return on investment.

Another benefit is that the surface finishing apparatus, whether it is a belt, wheel or disk device, can be quite large. Using longer belts, larger diameter wheels, and higher horsepower means that parts can be processed more quickly with longer intervals between media changes.

A final benefit is that fairly consistent compliance can be achieved with floor mounted, relatively inexpensive, passive (open-loop) compliance devices. Because the axis of compliance is fixed, tool weight compensation is constant. However, as will be shown later, there are additional benefits to having active (closed-loop) control as opposed to passive control in *Part in Hand* applications.

One disadvantage to *Tool in Hand* systems is that it is sometimes impossible to finish the entire surface of the part. This can be due to both interference with the robot gripper itself and insufficient robot dexterity to reach all around the part. Often the only solution to this problem is to place the part in an intermediate fixture and re-grasp the part in a different position.

Tool in Hand

Tool in Hand applications are currently less common in manufacturing than *Part in Hand* systems, however, recent advances in active force control technology provided the basis for a rapidly growing group of applications. *Tool in Hand* configurations are used where the part to be finished is too large or unwieldy for a robot to carry. In these applications a compliant tool is mounted to the robot and manipulated over the part to be finished. The tool can be either an active or passive device with disk or wheel type abrasive media. Belt media is rather rare in *Tool in Hand* applications because it is difficult to built compact tools using belts.

Less expensive passive force devices can be used where precise force control is not necessary. Therefore they are most useful for relatively flat contours or for rough de-flashing or grinding operations. This is because passive devices have open-loop control making it difficult to compensate for variations in the applied force as the robot moves the tool around the part.

On the other hand, active force devices with their closed loop control are ideal for *Tool in Hand* applications. These devices continuously compensate for acceleration and gravitational effects so that they can apply precise force levels in any orientation. Active devices, while more expensive, are able to tackle a wide range of finishing operations -- from rough grinding or sanding to fine polishing on a variety of materials. In addition, since these devices have a dedicated controller, they provide some unique advanced features which can greatly ease robot programming.

Because the abrasive media used with these *Tool in Hand* devices must necessarily be smaller, the media must be changed more often. Automatic abrasive disk changing equipment has been available for some time and allows the robot to change media without any human intervention.

Path Profiles

Robot motion for both *Part in Hand* and *Tool in Hand* applications involves smooth sweeping movements. There are three important aspects of the motion which have to be carefully considered in order to have a good finish.

Importance of surface speed

There are four process variables which most greatly affect the Material Removal Rate (MRR) in finishing operations. These variables are: the aggressiveness of the media, the force with which the media is applied, rate at which the media is fed (RPM or IPM), and the speed at which the media is moved over the part surface. Of these four variables, the robot has direct control of only the last.

It should be noted, however, that all of these variables can influence and offset each other when trying to achieve a particular surface finish while maintaining a desired process throughput. For example, a more aggressive media can be used with lighter applied forces at lower RPM so that a higher surface speed can be used to increase production rates. However this must be balanced with the fact that aggressive media does not produce extremely fine surface finishes. The one rule to remember regarding surface speed is that the more aggressively a part is worked on a given pass (i.e., aggressive media at high force levels with high rpm) the faster the surface speed must be to prevent overheating the part surface and media. With the capacity of today's surface finishing equipment, it is quite possible to completely melt an abrasive disk and backup pad.

Unfortunately there is no cookbook approach to determining the optimal combination of the process variables. Trial and error combined with prior experience seem to be the best method to determining these variables. The good news is that varying any of the four parameters is a relatively quick and easy thing to do during initial process studies.

Importance of Part / Tool Orientation

The relative orientation of the part and tool is very important in achieving a consistent, uniform surface finish. The overall surface appearance is directly affected by the consistency of location and shape of the area where the finishing media contacts the part. This area is called the *contact patch.*

The contact patch is "where the rubber hits the road." Therefore, no matter what configuration is used, *Part in Hand* or *Tool in Hand*, and no matter what programming method is used, manual teach by show or off-line simulation, maintaining a consistent contact patch is the single most important path programming consideration. In most finishing operations it is usually desirable to have the finishing media applied to the part surface at an angle varying from normal to the surface to three to five degrees off of normal depending on the type of media. Jim Davis at the University of Texas at Arlington performed a great deal of research studying and quantifying the degree to which media orientation to the part affects surface appearance. He found that variations as small as two degrees can be highly detrimental to the final surface appearance.

The problem is that on contoured parts it is often very difficult to estimate the surface normal by eye. This leaves the user with two choices, either take the time to painstakingly manually teach the robot path, or somehow digitize the 3D measurements of the part and use an off-line simulation package. Mr. Davis had excellent results with the digitization technique finishing broad aerodynamic wing surfaces in his research. And to assist in programming smaller parts such as door handles, water faucets etc., robot simulation companies have developed hybrid measurement / simulation environments where a user manipulates a “virtual” grinder attached to a coordinate measurement device over the small part. The simulator records these motions and then produces a robot program to duplicate them.

Importance of the Approach Vector

The approach vector is the means in which the part comes in first contact with the finishing media. This transition point often is where many surface finishing inconsistencies are found in the final part. The number one rule applying to the approach vector is to come in gradually. If one looks at how a person finishes parts, one would find that the person’s movements are characterized by sweeping motions with gradual, controlled setting down and lifting of the media. These gradual and controlled motions serve to “feather” the finish at the edges. Duplicating these motions with a robot should provide similar results, however there is one potential problem.

It is difficult for robots, not having a “human touch”, to compensate for such things as the inertia, stiction and oscillation often found in passive compliance tools. When using these tools extra care must be taken to provide exaggerated gradual approach vectors to prevent the passive tool from gouging into and/or “hopping” across the part. Either of these phenomenon would have a serious effect on the final finish.

Active tools, with closed-loop control, have the unique ability to all but eliminate these undesirable effects by giving robots a more human touch. These tools are able to automatically compensate for stiction and inertia effects in the same way as human operators anticipate these effects. As will be seen in the following section, “controlled compliance” can make path programming much easier and increase processing throughput.

Controlled Compliance

A relevant question at this point is “What is compliance?” The physical definition of compliance is, “the magnitude of displacement per unit of force.” Compliance is typically graphed with positional displacement along the X axis and force along the Y axis.

The Need for Compliance

The need for compliance in surface finishing operations is suggested by the fact that human surface finishing workers are inherently compliant, and that robot performed poorly in surface finishing applications until compliant devices were introduced. This leads one to believe that compliance is an integral requirement in performing surface finishing tasks.

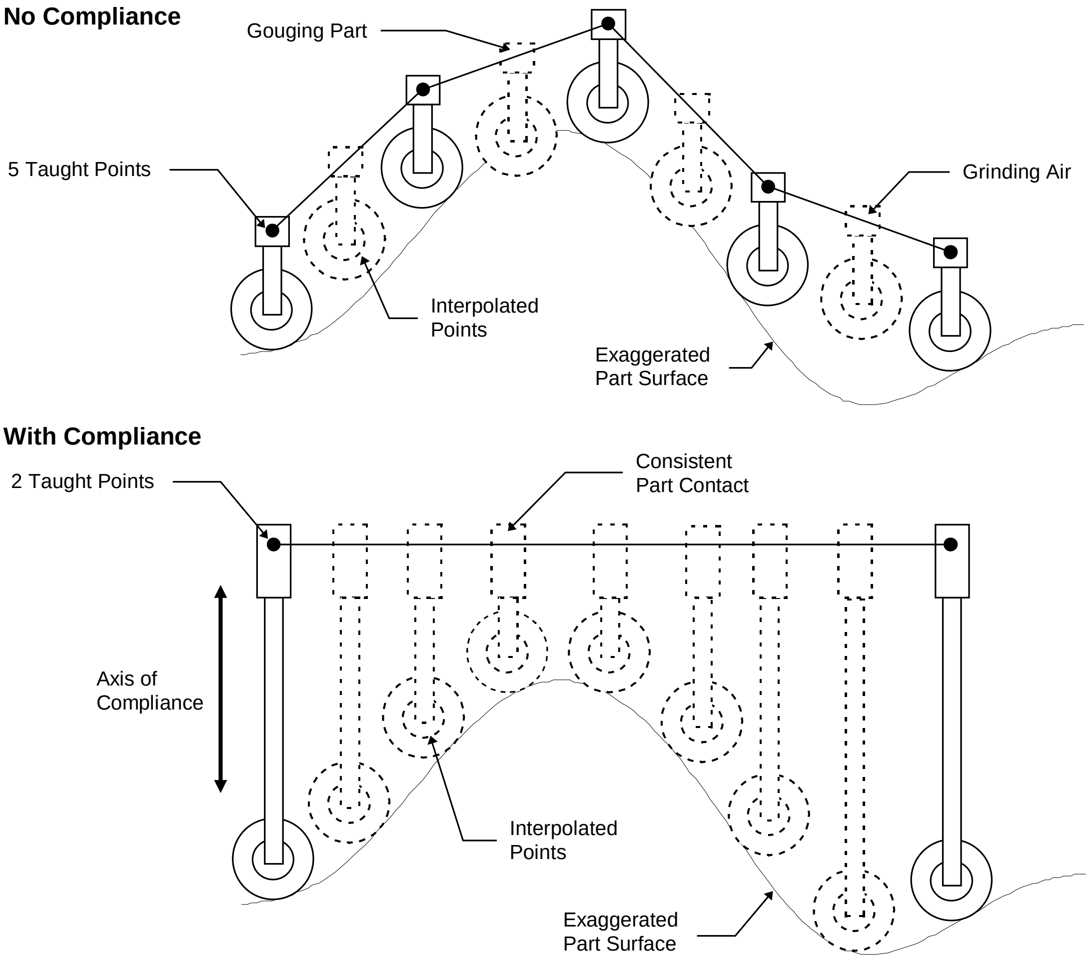

Figure 1. Effect of compliance on surface contact

Research has found that compliance is necessary because the material removal rate is highly dependent on the applied force. Compliance allows relatively stiff, position controlled robots to apply forces more consistently over irregular and contoured surfaces. Research has also found that compliance can compensate, to some degree, deviations in the robot path relative to the part surface as illustrated in Figure 1.

The top illustration in Figure 1 shows what happens as a non-compliant tool is linearly interpolated between taught points on a contoured surface. The surface contours in the figure are greatly exaggerated for clarity, however this effect exists on parts with even a slight contour. As shown, even though the path points are taught perfectly on the surface, as the robot interpolates between the points the grinding media's position relative to the part surface varies. On convex portions of the surface the media gouges into the part. On concave portions the media is not in contact with the part. On actual parts with slighter contours the varying contact can be detected by listening for variations in the grinding motor speed.

The usual way to minimize the interpolation problem is simply to teach more points allowing the media to more closely track the surface. This method can improve the situation as long as there is at least a little bit of compliance in the media. However, if a hard grinding wheel is used, teaching even hundreds of points might not be sufficient to produce a consistent part finish.

The bottom illustration shows the same surface but using an auxiliary compliant tool. With this setup it is possible to maintain consistent media contact with the surface with only a minimum number of taught points. Because the compliance is produced by an auxiliary tool, the system will produce good results whether or not the media has any inherent compliance. Therefore, introducing a compliant device creates two benefits: greatly decreased processed development time with fewer path points to teach, and a greatly improved finish resulting from consistent media contact force.

Types of Compliance

Currently there are several techniques to provide compliance in robotic surface finishing systems. Compliance built into the robot itself is called through-the-arm force control. This is because the degree of compliance, or the applied force, is controlled by varying the torque applied by the servo motors at each link of the robot. This method of force control is appealing because it eliminates the need for any auxiliary compliant tooling. However, through-the-arm force control has had limited success despite 20 years of research. This research indicates that through-the-arm force control works fairly well with very compliant media in low-speed applications, but performance deteriorates rapidly as feed speeds increase. This degradation in performance is due to the large mass of the robot arm and the finite amount of torque servo motors can supply.

Given the limitations of through-the-arm force control, “around-the-arm” *Part in Hand* and *Tool in Hand* compliance techniques have become much more common. Techniques for providing compliance in around-the-arm devices include spring actuators, electromagnetic actuators, and pneumatic actuators. Any of these techniques can used in both passive open-loop or active close-loop systems.

Spring actuation represents the most simple technique for providing compliance. With this technique compliant forces are achieved via the compression of a spring. Typically the force applied by a spring varies linearly with the deflection. See graph below:

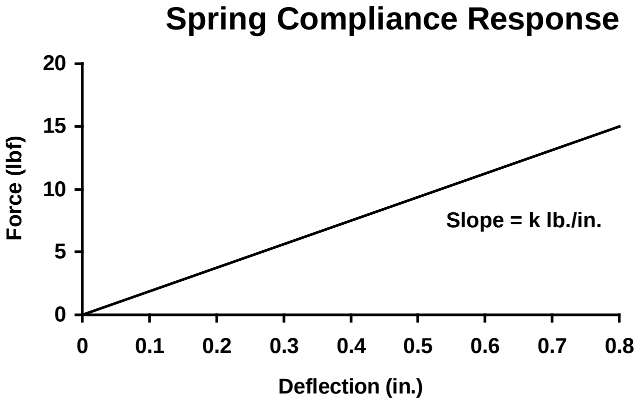

Figure 2. Spring Compliance Response Graph

In some cases the grinding media itself can be used as the compliance. Flapper wheels, brush wheels, and soft pads may be sufficiently “spongy” to be used as the sole compliance in a system.

For all their simplicity, there are a couple of drawbacks with any spring based compliant system. The first problem is that the applied force does change as the spring or media compresses. This change can be a linear change as with a spring or some non-linear change if the media is used as the compliance. This dependence of the applied force on the spring position can make programming the robot path over the part very critical. Steps must be taken to ensure that a constant spring compression is maintained in order to maintain a constant force. In applications where the surface profile can vary significantly and unpredictably, springs are probably not an option.

Other actuation techniques, such as electromagnetic and pneumatic actuation, eliminate the dependence of applied force on position. These methods are capable of applying a constant force over their entire stroke.

Electromagnetic actuation is an effective means to provide compliance. The force applied can be quickly changed by varying the electrical current flowing through a solenoid. The only drawbacks to this technique are that these solenoids are quite heavy and that they require a great deal of electrical power to provide significant forces. These drawbacks generally limit electromagnetically actuated systems to *Part in Hand* applications so that the compliant device can be floor mounted.

Pneumatic actuation is by far the most common means of providing compliance in commercial surface finishing systems. Pneumatics provide compliance by controlling the air pressure on either side of a piston actuator. Since the air compressor is located elsewhere, pneumatics can be packaged in light compact tools that even relatively small robots can manipulate effectively.

Pneumatic force devices are available in both passive open-loop and active closed-loop systems. In passive systems the piston air pressures can be controlled via manually operated or electrically controlled regulators. Passive systems are generally used extensively in *Part in Hand* applications because the tooling is attached to the floor and dynamic inertial and gravitational effects are of little consideration.

Active force devices build on passive technology by adding a force measurement transducer commonly referred to as a load cell. This ability to continuously measure the force actually being applied by the device combined with electronically controlled pressure regulators enables active devices to provide high precision compliance independent of spatial orientation, inertial, gravitational, and friction effects. These devices are used in both *Part in Hand* and *Tool in Hand* applications. And, as will be discussed in the following sections, they provide features which passive devices simply cannot match.

Benefits of Real-time Force Adjustment

Active force devices give one the ability to easily and predictably change the effective compliance of a tool in real time. Real time in this case means that compliant forces are monitored and updated as quickly as 1000 times per second. This feature gives users unprecedented ability to continuously adapt compliant forces to optimize material removal and surface finish as the process is running.

An example of this capability is the recently developed Graf Contour Mode feature. This feature makes it simple for users to utilize the full potential of real-time adaptation of compliance with active force devices. Conceived by Tim Graf of 3M Company, the Graf Contour Mode allows the user to shape the compliance of the force device in an infinite number of ways.

The basic operation of the Graf Contour Mode is as follows. As stated previously, the active force device continuously monitors and corrects the applied force. In addition, the device also monitors the position of the slide along the axis of compliance. The active force device uses these values to vary the applied force up to 1000 Hz as a function of the position of the slide. The Graf Contour Mode allows the user to assign different desired force values at each point as the slide moves from fully extended to fully retracted. In other words, the user can create and adjust their own complex compliance response dynamically in real-time. This feature opens many new processing possibilities compare to passive spring or pneumatic devices with their static non-adjustable linear or constant responses.

For example, one could use the following compliance response to minimize inertia effects and bounce when the tool contacts a part.

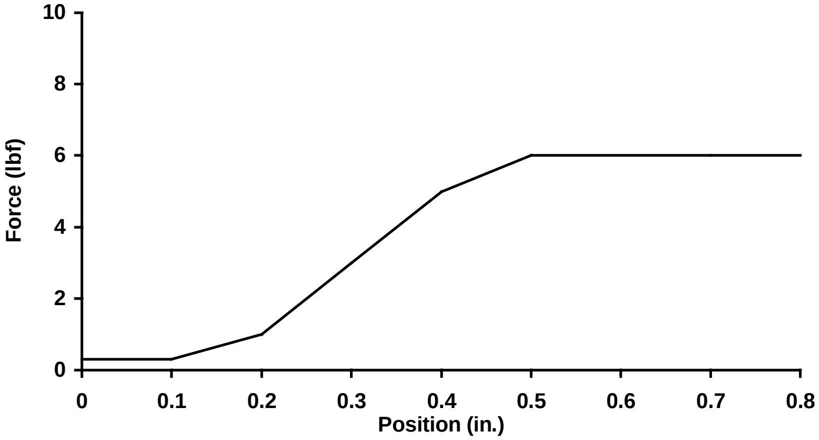

Figure 3. Compliance response to minimize bounce

The response shown in Figure 3 allows the force to gradually increase until mid stroke is reached. From mid stroke on the force remains constant at the desired force level. Note that a non-linear compliance such as this would be difficult if not impossible to achieve with any other non-active force control technique. The benefits of this sort of controlled compliance will be felt immediately since the robot approach path will be much less critical and higher speeds can be used.

Another clever use of the Graf Contour Mode is in de-burring or de-flashing parts. A key requirement in these applications is to remove the burr of flashing without over grinding into the part itself. This is especially difficult since often burrs and flashing are highly irregular and unpredictable in size. The compliance response shown in Figure 4 easily and automatically accomplishes this task.

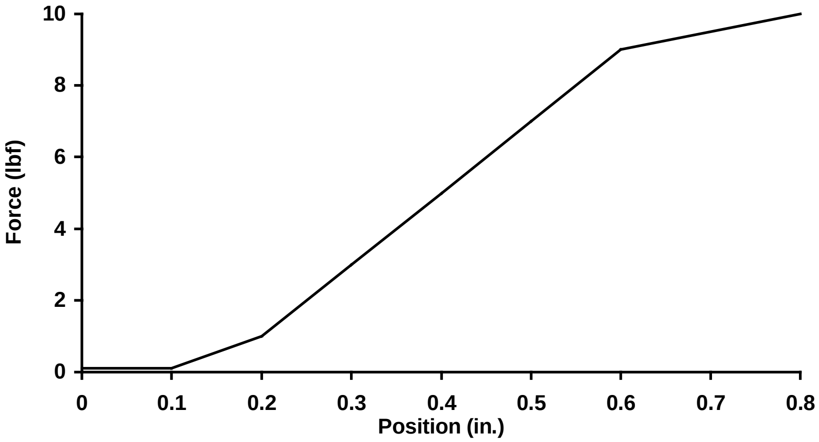

Figure 4. Compliance response to de-burr or de-flash

Notice that in this compliance response that the force goes to almost zero as the slide is nearly fully extended. To take off burrs or flashing simply program the robot to follow the nominal part contour on a part with the flashing removed. Now when a part with burrs or flashing is processed the height of the flashing will push the slide up into the region where more force will be applied, the higher the flashing the greater the force. But as the flashing is removed the force goes to zero precluding any possibility of over grinding the part.

Conclusion

This paper has discussed some of the factors which should be considered when programming surface finishing applications. When assembling an automated surface finishing cell one should take time to consider programming issues before selecting equipment. One should consider the relevant advantages and disadvantages in using a *Part in Hand* verses *Tool in Hand* configuration. One should consider the time to manually teach robot paths verses purchasing more advanced simulation systems to generate robot paths off-line. And finally one should consider the costs and benefits of using passive verses active force devices. After weighing all these factors, anyone can design a cost effective surface finishing system capable of producing parts of the highest quality.

Related Publications

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2 Lawley, T. J., Erlbacher, Edwin A., "Robotic Grinding of Parts to Remove Machine Tool Scallops and Mismatch," Maintaining and Supporting an Aircraft Fleet Conference, Dayton, Ohio, June, 1992.

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5 Erlbacher, E. A. " Robotic Surface Finishing Cell for Contoured Scalloped Parts," Ph.D. Dissertation, University of Texas at Arlington, 1992.

6 Davis, James C., "Path Planning Methods for Robotic Grinding of Complex Contoured Parts," M.S. Thesis at the University of Texas at Arlington, 1993.

7 Godwin , L. E., “Design and Implementation of a Modular Object-Oriented Integration Architecture for Real Time Systems,” ," Session Twenty of the International Robots & Vision Automation Conference, Detroit, Michigan, April, 1993.

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12 Wenzel, Dennis J., Mcfalls, David S., "An Optimal Material Removal Strategy For Automated Repair Of Aircraft Canopies," IEEE, 1989