What is 5-Axis Machine

This document discusses the need for five-axis machines as well as the benefits of these machines. The document also overlooks the kinematics of existing five-axis machines.

In material-processing one would require realizing arbitrary relative location (position and orientation) between the material (work-piece) and the material-processing tool (also called end-effector). Among many possibilities this material-processing tool could be a nozzle (eg for laser, water-jet, sand-blasting, painting ...etc), a spinning cutter (eg for milling as shown in Figure 1 or grinding ...etc), a sensing probe or a mechanized handle.

If material-processing is to be realized in a general manner, then the mechanism required to hold each of the material and the processing tool and then provide the relative motion between them would generally need to possess six Degrees Of Freedom (DOFs), which is the space DOFs. However, as the vast majority of material-processing tools are symmetrical about one of their axes, then orientation of that tool about that symmetry axis need not to be cared about or controlled. A five-axis, rather than six-axis, machine would suffice in these cases. Of course sometimes this symmetry does not exist and the need for each one of the six DOFs is there. There are even cases where more than six DOFs would greatly simplify the task and hence seven or more DOFs are adopted. Here, nevertheless, we are concerned only with five-DOFs machines as the need for them by far exceeds the need for mechanisms with higher DOFs.

Industrially, most of the existing milling and engraving machines are three-axis machines (see the machines of Figure 1 or Figure 1, with their Cartesian coordinates, as examples). Only the relative displacement is to be controlled in these cases. The relative orientation is no controlled. Given the large difference in price between three and five axis machines a business would usually sacrifices the work that would require the more expensive five-axis machines.
A five-axis machine allows the tool to reach five-faces of the work-piece. This is realized through the two additional relative rotations between the work-piece and the tool. Industrially conventional five-axis machines similar to the one shown in Figure 2 represent the vast majority of five-axis machines. Notice that the Cartezian coordinates are slightly different in the three examples presented so far. In one case (Figure 1) two DOFs are given to the end-effector and the third is given to the material, while in the other two cases (Figure 1 and Figure 2) the three Cartezian motions are given to the end-effector while the material
is kept stationary. In the latter case there are also variations in one case (Figure 1) the whole bridge carrying the tool is given the three DOFs and in the other case (Figure 2) only the cross beam of that bridge is given the three DOFs. There are many variations of these Cartesian DOFs and surveying these variations is beyond the scope of this document. The criteria in all these variations usually are minimizing the machine space and the power of the motors used, as well as maximizing the rigidity.

Now the focus turns towards the two incorporated rotary motions. As these two rotary motions need to have two axes that are perpendicular to each other, one can see the actual variations are limited. That is, either both of the two rotary motions are given to the tool, both of the two rotary motions are given to the material processed or one rotary motion is given to each of them.

Figure 3
Tool (End-Effector)
Fork-Head Design

Figure 24 to Figure 7 represent the absolute vast majority of the existing five-axis machines. The fork-head design of Figure 2 and Figure 3 and the swivel-head design of Figure 4 are two dominant designs where the two rotational axes are given to the tool (end effector). The
fork-head motion can be provided to the material as shown in Figure 5 and Figure 6, and so is the swivel-head motion as shown in Figure 7.

Figure 4
Tool (End-Effector) Swivel-Head Design

Figure 5
Material Fork-Head Design

Figure 6
Material Fork-Head Design

Figure 7
Material Swivel-Head Design
**Why 5-Axis Machine**

- **Reaching tilted/side planes.** That is, tilted with respect to the X-Y plane. This is another way of saying 5-face machining.
- **Maintaining better cutting quality.** This is because the optimum orientation from point of view cutting angles can be maintained. That is, certain cutting process can be realized just by varying the z-value. However, as the cutting process proceeds new planes that not parallel nor normal to the X-Y plane are created. Tilting the cutter will allow maintaining the desired relative orientation between these new planes and the cutter.
- **Realizing more intricate details.** A cutter with conic shape can allow realizing more cutting depth of an intricate contour. In the figure below, if the width of the contour is 1mm, then a cylindrical tool will be able to go may be only 3 or 4 mm deep and the shank of the tool in this case would be 0.8 mm. On the other hand a conic tool that is tilted as shown in Figure 9 below can have a larger shank for the same depth of cut and contour width.

---

**Figure 9**
Conic Tool and 5-axis to realize finer details
Ideal 5-Axis Machine

One can see that it is not a trivial task is to mechanically align a five-axis machine. The machine has three Cartesian axes similar to the ones Figure 1 or Figure 1. The extra two DOFs are provided using two revolute joints that are carrying heavy masses. The final error at the end-effector is the accumulation of all the joints and alignments errors, and hence rigidity-design and then accurate assembly of such a machine to enable quick and precise end-effector motion is a really difficult task. The difficulty does exist, but adds to it the fact that the rigidity is a mechanical engineering task while speed control is not.

In reality the five-axis machines mentioned so far suffer (the swivel-head to a lesser extent) from the problems of heavy weight, lack of bearing stiffness and long swivel length. Their most severe disadvantage though is their inability to perform high-speed tasks. This is especially true when a small radii need to be covered, as shown in Figure 10. If the motion/contour speed is required to be maintained at certain value, because of the geometry/kinematics of the design the joints speed and acceleration needs to go to very high values at the corners particularly when the path curvature increases (ie as the curvature radius decreases). The situation gets even worse when the swivel length increases, as demanded by some applications. Moreover the mechanical design is incapable in the first place of high speed and high accelerations because of its weight and stiffness problems.

![Figure 10](image)

**Figure 10**

Machine Geometry/Kinematics is demanding high joints speed and acceleration
Remarks

- The two rotational axes of any of the designs above (Figure 3 to Figure 7) can be aligned with any two of the three Cartesian (X, Y and Z) axes.
- The radius to be covered and the swivel-length influence the desired joint speed exponentially.
- Quickness sought does mean that the five-axis mechanism needs to travel at highest possible speed, acceleration and jerk (rate of change of acceleration). Acceleration and jerk are actually as important as speed, as in many cases the travelled distances to accomplish the material-processing task are short. In these cases the mechanism is accelerating and decelerating all the time without reaching the allowable speed/velocity.
- In extreme cases both quickness and accuracy/precision are needed simultaneously.

Figure 8
The Four Basic Coordinate-Systems-Based DOFS
The previous shows that low-stiffness, excessive-weight, slow-motion, alignment-difficulty do represent problems that are difficult to resolve using the traditional approach. Some of these problems can actually be solved at high cost. Stiffness and quickness are not possible to resolve though in most cases.

Figure 8 shows the kinematic fundamentals upon which all the above machines were built. To realize three DOFs one would rely on mimicking one of the commonly used Cartesian (3 rectilinear coordinates), Cylindrical (2 rectilinear and 1 rotary coordinates), Spherical (2 rotary and 1 rectilinear coordinates) and Revolute (3 rotary coordinates).

Figure 9
Combined or Replicated DOFs

(A) SCARA
(Selective Compliance Assembly Robot Arc)
DOFs

(B) Combined Cylindrical and Revolute DOFs

(C) Replicated Revolute DOFs
To realize fives DOFs, one would attempt to replicate or combine any of these four coordinate-systems-based DOFs. Examples of that are shown in Figure 92.

All the mechanisms of Figure 8 and Figure 9 have their DOFs arranged serially one after the other. Figure 2 to Figure 10 together with their associated argument showed that arranging only two rotary DOFs serially will lead to the many problems mentioned above. One can imagine what would happen when more rotary joints are arranged in serial. For this reason all the mechanisms of Figure 8 and Figure 9, or their variations, are not expected to resolve the five-axis machine problems mentioned above.

At Simplex we believe that the solution to the problems of the 5-axis machines above is our SimParallel machine. The one shown below in Figure 13. More about this machine can be found in www.simplex-cnc.com.au

*Figure 13*
*SimParallel The Right 5-Axis Machine*