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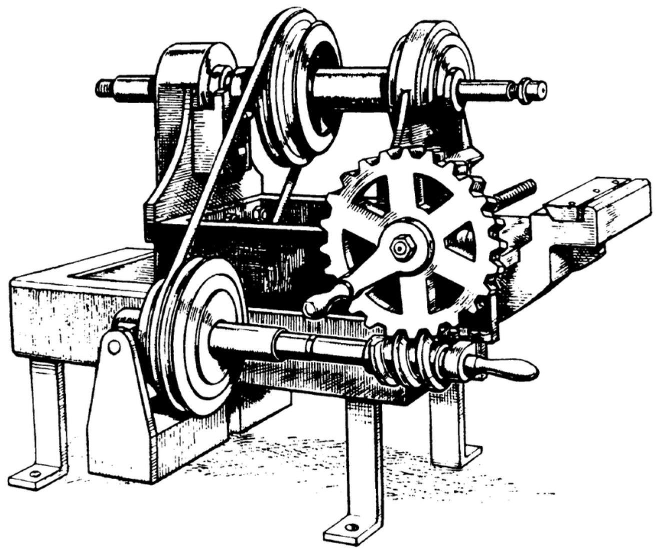
5-Axis Mills

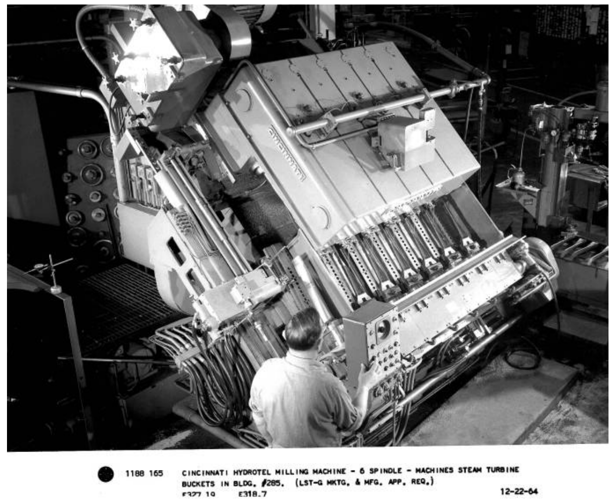
Numerous of the world's most complex parts, ranging from jet engine turbines to medical devices, are manufactured using the technology of CNC mills, and depending on the part can only be produced at scale with the aid of five-axis mills. On the most fundamental level, a milling machine is a manufacturing tool that contains both a cutting tool that can cut away material, and one or more axes that the cutter or part can move along. By cutting away at the material following a set path, a block of material such as metal or wood can be cut away precisely to create a part.

The history of milling machines has been suggested to date back to the American inventor Eli Whitney in 1818 (Banka 2017). Known largely for inventing the cotton gin, Whitney was awarded a contract to manufacture rifle parts. Whether or not Eli Whitney was the first to actually develop a milling machine is largely disputed by historians, but it can be concluded that it was around this time milling machines began to be developed by Americans for the mass production of parts (Baida 1987). Due to the stipulation that the rifle components had to be uniform to be interchangeable, and produced at scale, milling machines that could cut from patterns were created for this task. Utilizing a series of gears and cranks, these early machines could cut metal along a preset pattern which enhanced the scalability of producing reproducible parts under the threat of war.



*An illustration of one of the earliest milling machines, circa roughly 1818, often credited to Eli Whitney (*Computer 2022*)*

The first style of early milling machines was largely untouched for a considerable amount of time, and it was only in the 1950s that the modern advancements of 5-axis milling machines occurred. Prior milling machines were highly dimensional, with a lot of wood-turning machines having up to 12 axes all controlled by gears, but they were largely manual (Applications 2022). Coinciding with the dawn of computing, CNC machines began to emerge. The Cincinnati Milacron Hydrotel was the world's first CNC milling machine, and it was developed by MIT and the machine company Cincinnati Milacron. Utilizing hydraulics for axis movement, and tape libraries for CAM programs, the Cincinnati Milacron Hydrotel revolutionized machining and was the baseline for all modern machines (The History 2019). Software and engineering have continued to advance and machines are now highly precise and versatile with modern CAD software.



*The Cincinnati Milacron Hydrotel machine (*Banka 2016*)*

Modern mill machines work by using a cutting bit that is moved along an axis. A single-axis mill can be thought of as a drill press, where the cutting bit is simply moved up and down relative to the part. Simple mills are usually 3-axis, where a cutting bit can be moved along an X and Y axis as well as up and down along a Z axis. These mills can be manual or automated and can produce most parts. The main limitation of a 3-axis mill is that material cannot be removed if there is an overhang. Take the simple shape of a sphere as an example. The top half of the sphere could be cut out, but the bit would be unable to reach the bottom half of the sphere to cut the material away as it would be blocked by the sphere itself. To get around this, the machining can be temporarily stopped and the part can be manually turned so the unreachable area is exposed to where the bit can reach. This process of stopping the manufacturing process to rotate parts is time-consuming, however, and can lead to inaccuracies in the part.

Five-axis milling machines resolve this issue. The cutting bit remains moving in 3 dimensions as before, but the part which was originally fixed can additionally be rotated along 2 additional axes. By moving the part, the need to manually change the orientation of the part is eliminated. Regions of the part that originally would have been blocked by overhang are then exposed and can be cut away. By keeping the part rotating with the cutting bit, 5-axis mills can generally produce much more precise parts with smoother surfaces as the rotation of the cutting surface can be continuously moved (John 2023).

For metal parts, casting, forging, and milling are the three main forms of manufacturing practiced today. For complex and precise parts, milling is the best choice and 5-axis milling is the industry's best method. Production-level mills are extremely advanced and are worth over half a million dollars for one unit (Computer 2022). These machines are capable of producing thousands of parts with accuracies down to a thousandth of a millimeter.

Modern milling machines, including 5-axis CNC mills, are found in manufacturing applications around the world. Top manufacturers of these machines include Haas Automation, DMG Mori, and Mazak, all of which are part of this roughly 100 billion USD industry (Computer 2022). Use cases are vast. In the aviation industry, for example, companies like Boeing use 5-axis milling machines along their whole production line. Often built as one-offs, in these types of production settings, such milling machines are often custom for the part they are producing and serve to do just a singular step along the production line. Factors such as part size and shape are taken into account and milling machines are created to accommodate specific specifications. In the R&D process, more generic 5-axis CNC machines are used to develop parts for advanced prototypes and special use cases (Perry 2018). These machines are all highly specialized for making accurate parts quickly. Special features such as automated tool changing and cutting techniques allow for the quicker production of parts. The quicker the machine, the more profitable it is as more parts can be produced.

As one of the most advanced manufacturing tools in the world, cost, and complexity are both big limitations to these tools. Advanced software is helping take care of some of the complexity in use, however, with automatic path tracing and optimizations being generated programmatically. As these machines advance and get better, they are slowly coming down in price and working their way into less specialized roles. Just as has happened with additive manufacturing, eventually it could be feasible for these machines to be more accessible to hobbyists and widely deployable. For now, they remain in use for advanced use cases and professional applications, with nearly any part manufactorable from their tooling.

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