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3-Dimensional Layered Path Planning for Anytime Milling Applications

Purpose

We present an automatic path planner for a robotic milling system in orthopedic surgery. Miller shaft alignment is restricted to be vertical, therefore the milling volume must be non-undercutting, i.e. the whole surface must be visible in the view from above and below. The system has anytime ability, i.e. milling can be aborted prematurely and the object still fits into the mould.

Material and Methods

The milling volume is given as a triangulated geometry and is discretized into a voxelspace. Because the voxelspace's resolution can be chosen higher than the robot's absolute accuracy, planning on a voxelspace does not result in a reduced quality of the planned paths.
The actual volume to be removed differs from the volume where the tool center point has to move along in principle. We approximate the milling head geometry with a rastered sphere, but other shapes can be used as well. A distinction is made between "contour destroying milling" (the whole volume has to be removed, so generally there are transgressions) and "contour preserving milling" (no transgressions allowed). The actual milling volume within which the milling head shall move is created from the initial volume; the latter is not considered anymore.
As a path length and operation time optimization, the surrounding milling material can be modeled too (e.g. via 3D imaging) to obtain an "individual milling volume" smaller than the "generic milling volume". Regions outside the material need not be milled.
During further path planning, only the lower contour of the volume is considered. In each iteration of the planning process, this contour is lowered incrementally into the milling material. This way, anytime ability is ensured. The lower contour is subdivided into horizontal layers for which path generation is performed separately. Path planning in the inner areas of the contour is based on a rougher grid than in the areas close to the border, allowing inner areas to be milled more quickly.
We have implemented three path generators: contour-parallel, linear and potential field based.

Results

The planned paths are used to perform surgical operations in the lateral skull base (temporal bone). Experiments show that the geometry is milled precisely (the error is in the dimension of the robot's absolute accuracy). Often, the generated paths are angulated, having a negative impact on the milling speed.
Experiments with still unsmoothed paths yielded a path length of 4.67 metres and a milling duration of 10:58 minutes for the Combi40+ implant by Med-El and 6.01 metres and 19:17 minutes for the Vibrant Soundbridge by Med-El/Symphonix. However in the meantime the paths are considerably smoother and shorter.

Conclusion

We have developed a planning system which allows to generate paths that can be milled automatically with anytime ability, using a vertically oriented miller. The modes "contour preserving" and "contour destroying" are implemented, as well as a path length optimization which uses the milling material geometry.