Concept for collision avoidance in machine tools based on geometric simulation and sensor data

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Abstract Collisions are a major cause of unplanned downtime in small series manufacturing with machine tools. Existing solutions based on geometric simulation do not cover collisions due to setup errors. Therefore a concept is developed to enable a sensor-based matching of the setup with the simulation, thus detecting discrepancies. Image processing in the spatial and frequency domain is used to compensate for harsh conditions in the machine, including swarf, fluids and suboptimal illumination.

Keywords Manufacturing, collision avoidance, frequency domain

1 Introduction

In order to remain competitive in a global market, manufacturing is under pressure to continuously improve quality, costs and flexibility. There is a trend towards more variety in the final products, leading in turn to smaller batch sizes in production, including single-part production and mass customisation [1]. To be able to produce such parts in an economic way, it is necessary to optimise different stages of the production process. During the preparation phase, the planning and setup effort need to be minimised, which relies heavily on experience: skilled workers know how to setup production for a new batch and experienced engineers are needed to safely plan the manufacturing process. The scarcity of these skills and the cost of training increase the need for support from digital solutions. New CAM (computer-aided manufacturing) software concepts help to detect problems during process planning, but show deficits when used in an Industry 4.0 environment [2]. The concept of a Digital Twin connects digital process planning with information retrieved via simulation or sensor measurements of the real process [3].

Another approach is to optimise the process on the machine level, for example by reducing downtime through condition-based maintenance and process monitoring [4,5]. One major cause of downtime are collisions between machine parts and production equipment, especially in small series manufacturing [5]. When correctly used, a Digital Twin allows to use advanced CAM algorithms to avoid some collisions already during the planning phase [6]. Other types of collisions cannot be detected in advance due to the potential for human error during the frequent and highly manual operation of setting up fixtures and workpieces [7]. This can be prevented by using a collision avoidance system. To apply such a system, all geometric features need to be modelled correctly by hand or via importing machine geometries and additional elements through given process-planning data. The placement of these elements must be precise to ensure that collision checking and avoidance algorithms work correctly. This is especially the case for the workpiece, fixtures, and other supporting elements, as their geometry or position within the machine can change after the planning stage. To overcome these problems, the present contribution proposes a concept for collision avoidance consisting of a combination of geometric simulation and sensor-based inspection, thus avoiding collisions caused by discrepancies between simulation and real contents of the work area.

2 State of the art

Existing solutions for collision avoidance in machine tools can be divided into the following categories: collision check during process planning, simulation-based dynamic collision avoidance, camera-

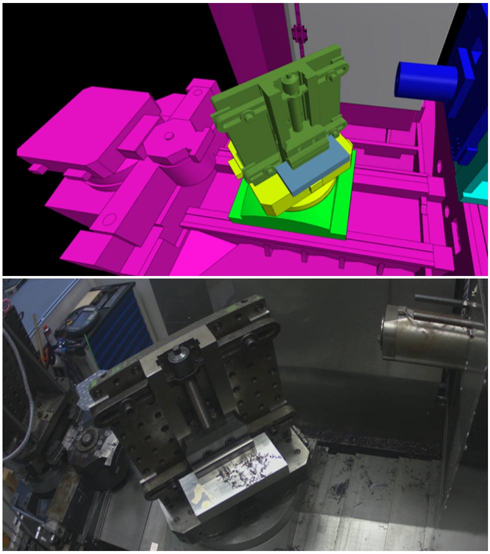


Figure 2.1: Simulation (top) and camera image (bottom) for an exemplary setup.

based monitoring, and monitoring based on distance measurement. Collision check during process planning is a widespread and commercially available approach, in which a geometric model of machine tool, fixture, workpiece, and cutting tool is used to simulate and verify the planned machining steps [8]. In dynamic collision avoidance, a similar geometric model is used to check for collisions (Figure 2.1), however it is integrated in an in-time simulation running during machine operation based on real-time and look-ahead data from the machine control unit [9]. These systems come in two flavours. They either check only for collisions between moving but constant geometries, or they also consider the changing geometry of the workpiece by simulating the material removal in real time as well.

Camera-based monitoring approaches aim to detect discrepancies between the real contents of the machine's work area and a reference geometry (either the geometry used to check the program during process planning, or the situation when previously manufacturing identical parts). Existing solutions for camera-based monitoring either overlay images from the geometric simulation and the real situation in the machine, and rely on a visual check by the operator [10], or rely on reference images from previous parts of the same type [11]. Monitoring based on distance measurement relies on laser triangulation, ultrasound, or inductive sensors to check the distance between moving parts of the machine (e. g. the main spindle) and obstacles such as the fixture and workpiece [12], however the position and number of sensors is limited due to high costs and limited mounting space.

Another approach to reducing costs due to collisions is collision detection. Acceleration, force or motor current signals are used to detect impacts and unexpectedly high loads, following which the movement of the feed axes is stopped as quickly as possible. This can limit the resulting damage to the machine, thus reducing repair costs and downtime [13]. The approaches described above either require a visual check by the operator, don't cover errors in setting up fixture and workpiece, require significant effort for sensor integration, require reference images from previous manufacturing of identical parts, or aren't able to entirely avoid collisions.

3 General approach

The present approach aims to combine the advantages of simulation and sensor-based approaches in a cost-effective solution for collision avoidance focussing on small-series and single-part manufacturing. In this context, it is especially relevant to ensure the first produced part is a good part, with minimal effort for setting up, running-in and human supervision. The combined system aims to detect mistakes in setting up or in the geometry model as well as discrepancies occurring during manufacturing (e. g. different workpiece shape due to a broken or wrong tool in a previous step, displaced workpiece due to inadequate clamping). The geometry of machine, fixture, workpiece and tool are modelled in the simulation-based collision avoidance system ModuleWorks CAS, and the model is updated during machine operation based on data from the machine control unit and a material removal simulation [9]. The data obtained from the

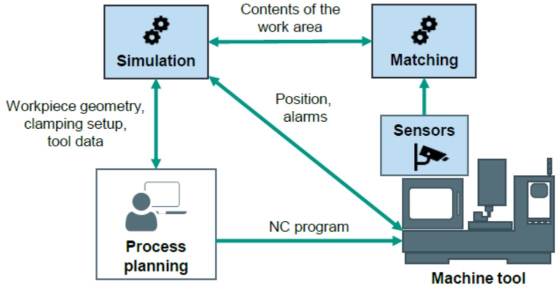


Figure 3.1: System architecture.

control unit comprises all the information necessary to simulate the current and the future state of the machine within a certain time span. Besides pure axis data, this also includes information on states in which the tool should not be allowed to cut material (e. g. during rapid movement or jog movements). If a future collision is detected based on the look-ahead data in the simulation component during automated movement, an alarm is sent to the machine to enable the feed axes to be stopped in time. During manual jog movement, the feed is controlled in such a way that the machine slowly approaches a future collision situation and finally stops before the contact occurs.

In order for CAS to work properly, the setup in the machine needs to be correct at all times. The workpiece in particular must be placed with a high accuracy to allow for safe process conditions. The level of accuracy required depends on the machining process, ranging from below one mm to orders of magnitude smaller. The lower end of this range cannot be checked with contactless sensor data alone within a cost-effective solution. For the placement of fixtures and the workpiece, the system therefore provides the possibility to position objects to a work offset measured by a probing process, which is usually also required to setup the machining process itself. However, the probing process is also prone to collisions because the initial position of the objects still has to be entered manually or based on information from the CAM project. At this stage, but also during the machining process itself, CAS is enhanced by a continuous sensor-based validation of the modelled situation. To accomplish this, the simulation component of the collision avoidance system periodically transmits an image of the current geometric model to a separate software system, which is tasked with matching the geometry from the simulation with sensor data acquired in the machine's work area (Figure 2.1). If a discrepancy is detected by the matching algorithm, an alarm is sent to the machine control unit. An overview of the resulting system architecture is shown in Figure 3.1. The approach is tested in the machining centre DMC 60H, though care is taken to develop a solution that is applicable to a wide range of machines. The following section is dedicated to the image processing within the matching algorithm.

4 Image processing

In the first prototypical implementation of the concept, a single camera with a resolution of 1920x1080 pixels is used to observe the machine setup. Simulation-based collision avoidance typically allows for a safety clearance of 3 mm between bodies in the geometric model. In order to detect all critical discrepancies, the measurement and matching in this approach aims to detect deviations of 1 mm or more from the simulated geometry. If required due to the manufacturing process, smaller deviations could then be handled by probing. Damage during probing can be avoided thanks to the previous matching based on camera images.

The aim of image processing within the collision avoidance system is to detect the contours of fixture, workpiece and other obstacles in a sufficient quality for a subsequent comparison with data from the geometric simulation. The conditions in machine tools lead to challenges due to obstruction by swarf (metal chips resulting from the cutting process, ranging from small particles to long tendrils), fluids (oil and coolant), and suboptimal lighting conditions. An example of a workpiece partially covered by swarf and coolant is shown in Figure 2.1. For each of these challenges, suitable image processing methods are evaluated using images acquired in the machining centre DMC 60H.

4.1 Spatial domain

The present approach uses processing in the spatial domain to detect the contours of fixtures and workpieces through Canny edge detection, and to compensate for the influence of lighting and fluids. As no object detection or semantic segmentation has been implemented yet for this application, the region of interest for cropping was selected manually.

The conditions for image acquisition in machine tools can be improved by adding light sources, however the structure of machine tools and the presence of reflecting metallic surfaces mean undesired artefacts due to reflection and shadows remain frequent. Two light sources are used to successively illuminate the scene from different angles. In the resulting images, the position of artefacts linked to the illumination changes. This effect is used by removing edges that do not appear in the same position in both images (within a tolerance of one pixel). The result is shown in Figure 4.1.

Coolant and cutting oil are frequently used to lubricate and cool machining processes. These may cover patches of the workpiece or fixture, thus causing additional edges in the captured images and hampering the detection of contours. The present approach uses the following steps to identify such additional edges:

- Bilateral filter
- Segmentation based on thresholding of pixel colour to identify coolant
- Adding similarly coloured neighbouring pixels to the segment
- Dilation of the identified segment

The original image is subjected to Canny edge detection, then all edges within the identified segment are removed. An example for this procedure is shown in Figure 4.2.

4.2 Frequency domain

Additional image processing is performed in the frequency domain, with the aim of removing edges due to swarf and other causes such

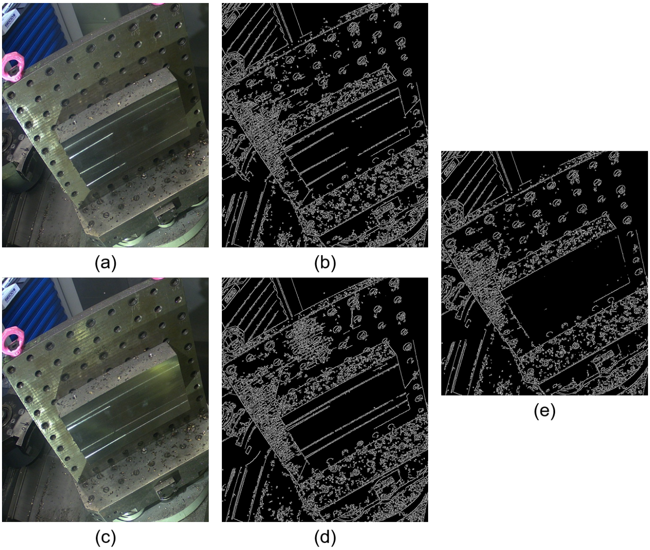
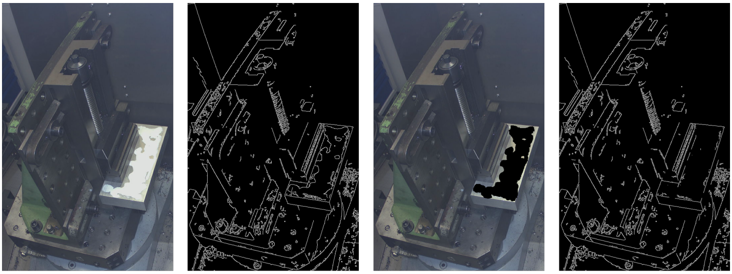


Figure 4.1: Removal of additional edges due to lighting. Images taken while varying the lighting (a, c) display additional edges due to the lighting conditions (b, d). These are identified and removed by comparing the images, thus leading to the improved image (e).

as scratches, chipped painted surfaces, and corrosion. These undesirable features are linked to randomly oriented edges and high spatial frequencies (Figure 4.3).

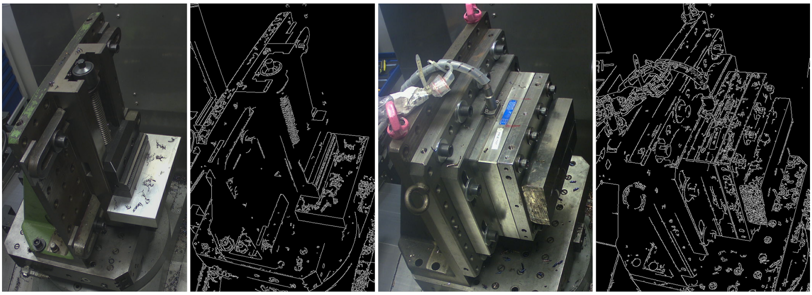
After using the 2-dimensional discrete Fourier transform (2D DFT) on the original image, the logarithmically scaled amplitude spectrum is subjected to a filter mask. After inverse 2D DFT, Canny edge detection is performed on the filtered image. The filter mask aims to select the dominant directions in an image and eliminate high frequencies, it is generated automatically for each image.

The dominant directions in the image appear as lines in the amplitude spectrum. The spectrum is binarised based on a threshold k, then the number of white pixels is counted for each line passing through the centre of the image, thus creating a histogram of directions. This histogram is smoothed by applying a moving average,



(a) (b) (c) (d)

Figure 4.2: Removal of additional edges due to coolant. (a) Original image with coolant; (b) Edges detected in original image; (c) Coolant identified and marked in black; (d) Image after removal of edges due to coolant.



(a) (b) (c) (d)

Figure 4.3: Examples of original images containing swarf and edge images without filtering.

then local maxima with a prominence of at least p are determined (Figure 4.4). The filter mask for dominant directions is the union of the following:

- Stripes with a width of b around each of the identified dominant directions,
- A disc with a radius of r_1 in centre of image.

The complete filter mask is the intersection of the above with a low pass filter (with a radius of r_2). Figure 4.5 shows the resulting im-

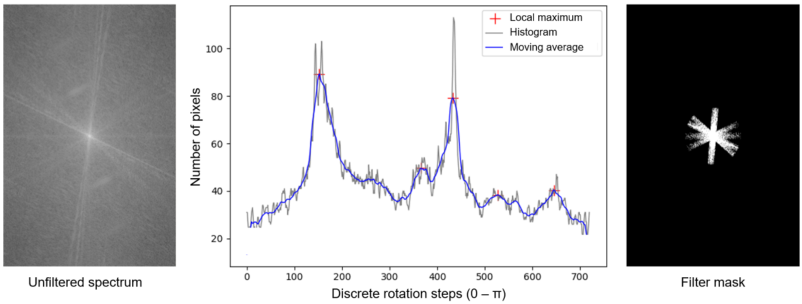


Figure 4.4: Selection of dominant directions in the amplitude spectrum, applied to Figure 4.3a.

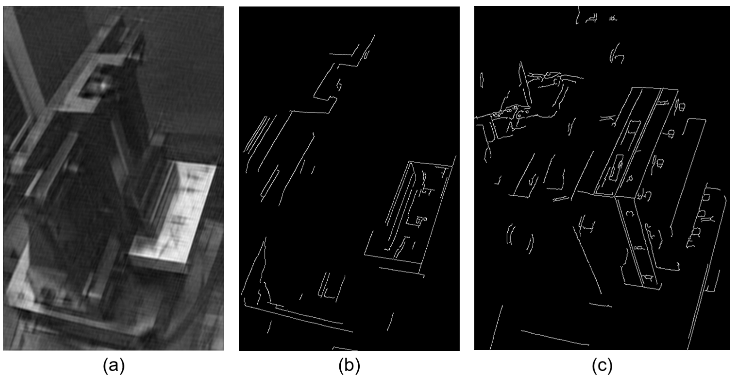


Figure 4.5: Results after filtering. (a) Fig. 4.3a after filtering in frequency domain and inverse transformation; (b) Edges detected in Fig. 4.5a; (c) Edges detected after filtering of Fig. 4.3c.

ages after filtering, inverse DFT and Canny edge detection for the examples from Figure 4.3.

The parameters k, p, $r1$, $r2$, b and the parameters for Canny edge detection are determined manually based on a representative selection of images, whereas the automatically generated filter mask adapts to scenes with different orientations.

5 Summary and further work

A concept was developed for a collision avoidance system covering a larger range of collision causes than existing solutions and especially well-suited to small series and single part manufacturing. The proposed system runs during the operation of a machine tool and combines a state-of-the-art geometric simulation with a sensor-based inspection of the work area. The encouraging initial results presented in this contribution concern the processing of images acquired in the harsh conditions of a machine tool's work area. Further work is needed to perform a wider evaluation for a representative selection of workpieces. The authors also plan to implement automated object detection and extend the concept in order to adjust the simulation model and tool path to the measured reality of the working area.

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