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Please provide details on how the project pertains to applied research:

**Background introduction**

Industrial robot is eligible for a wide range of manufacturing operations due to its high flexibility and versatility. More and more industrial robots are being employed for specific processing tasks such as painting, polishing and milling. By the year of 2015, over 1.5 million industrial robots (most of which are of 6-DOF articulated configuration) have been applied worldwide for various manufacturing assignments. Like the traditional computer numerical controlled (CNC) machine, in order to fulfill a certain operation/movement, industrial robots are executed based on a standardized programming language which specifies the discrete position along the desired path. To be more specific, the form of the program flow is essentially a list of instructions that define both the motion and the control settings for the robot. Typically, there are three methods to facilitate the robotic programming:

* Teaching pendant: teaching pendant is a dedicated controller which accepts manual input commands to control the robot. This handheld box is adequate for simple tasks such as moving from one point to another, but impossible to program a complicated task within an acceptable amount of time.
* Teaching by demonstration: robots that incorporates a “teach mode” can be programmed by demonstration from human beings to accomplish certain tasks. This demonstration is done by either dragging the robot or a joystick attached to the robot. However, accuracy is not guaranteed when the robot is expected to precisely move to a particular point, which may cause degraded process quality.
* Offline programming (OLP): offline programming is usually done virtually in a 3D graphical environment. When programming certain operations, predefined strategies are utilized to generate the complicated robotic motions with the highest achievable accuracy. The brand-specific post processor will interpret the motion into the circular coordinates of each joint which physically drive the robot. The offline programming will be the ultimate choice especially when the robot undertakes precision manufacturing jobs, which will be fully investigated in this project. However, current offline programming systems are still packed with deficiencies, as will be elaborated next.

**Existing deficiencies**

Based on our investigation on several commercial OLP software, when it comes to surface processing tasks such as finish milling or polishing, current OLP systems cannot offer a competitive solution compared to the CAM systems in traditional five-axis CNC machine. The major issues to prevent the robotic manufacturing from being popularizing are listed below:

(1) Lack of robust algorithm for collision check

Most of OLP systems are equipped with collision check module, which incorporates efficient collision check algorithms to generate interference-free robotic motions. However, due to the inconsistent and simplified representation of the virtual platform, collision is still a potential threat in real cases. Verification cutting test is always needed prior to the execution of the operation. How to faithfully represent the robotic system while still maintain an efficient and robust collision calculation will be our target in this project.

(2) Unacceptable accuracy

Unlike CNC systems whose translational axes travel linearly along X, Y and Z coordinates, the typical 6-DOF robot approximates a linear motion via a complex inverse transformation of a combined circular motion of each joint. Given this, the accuracy cannot be guaranteed when it dominates. The generated smooth tool path may turn out inferior in physical execution. Most OLP software in their current version cannot predict such accuracy in the tool path generation stage. On the other hand, the collision constraint could further deteriorates the machining accuracy when the system tries to resolve the interference by making a detour of its posture.

(3) Unsmooth tool orientation change

Due to the high non-linearity and the singularity property of the robotic system, a small change of tool orientation could be exaggerated to a drastic motion of the joint. As a result, the tool orientation planning for a complex milling operation is quite conservative and obsolete, with much less room to get optimized. Even though the exclusive post processor can resolve a majority of the unsmooth posture change, it would be much better if the OLP system can eliminate this issue earlier by a predictable path generation strategy.

(4) Lack of robot kinematic intelligence

In addition to the inaccuracy and unsmoothness caused by the lack of kinematic knowledge, it is impossible to optimize the machining efficiency without knowing the kinematic capacity (maximum velocity and acceleration) of each joint. When it comes to batch production, efficiency is always the primary objective. The lack of robot kinematic intelligence will lead to an obscure performance of the robot, thus may possibly cause a longer processing time.

(5) Lack of intelligent tool path generation algorithm

In contrast to the numerous options offered by the CNC programming system, the tool path generation strategies for robotic manufacturing are fewer, since these strategies have to be versatile to accommodate various operations. However, existing tool path as a result of the projection based algorithm is far from being optimized, especially when all the earlier mentioned issues are taken into account. More dedicated tool path algorithms for polishing, painting and milling, etc. should be devised separately according to their own attributes and requirements.

**Project objective**

To address all the aforementioned issues, this project aims to develop a more intelligent OLP system, which involves some fundamental research to tackle the problems. In addition to the stepwise milestones which are listed in part II, from the technical perspective, research will be focusing mainly on the three objectives:

1. Modeling of the robot kinematics and its relationship with the tool path.

2. Optimal tool path generation strategy for different applications, while considering the kinematic property.

3. Enhancement of the overall efficiency and accuracy in the tool path strategy.

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Please provide details on the viability of the proposal from the technical perspective, including R&D methodology to achieve each milestone, details of each milestone and the responsibility party, preliminary research results and supporting data, and the targeted results.

The OLP system to be developed aims to provide viable and efficiency optimized solution for the tool path planning of multiple manufacturing processes (including milling, polishing and painting) on a user-defined 6-DOF robot platform, and for an arbitrary shaped part. Based on these requirements, the system needs to incorporate the following algorithmic modules:

1. A 3D graphical engine and platform that supports a user-defined robot and its specifications, simulations and fast collision check.

The graphical engine is being developed based on AnyCAD, which is open sourced for developers to create and render 3D models. A database that comprises a variety of pre-defined articulated robots from popular brands will be incorporated into the platform to facilitate user interactions. Besides, the engine will also support a standard build file, which specifies the geometric details such as the shape and the joint range of the 6-DOF robot. Upon customizing a robot, the build file based design will be the most time-effective way.

As for the fast and accurate collision check between the tool/robotic arm and the workpiece, the dedicated oriented bounding box (OBB) data structure [1] will be appended to each activated geometry to calculate the interference in real time.

2. A surface partitioning strategy to divide the given geometry (represented as a 2D manifold) into smaller and more uniform surface patches, according to the processing/geometric requirements.

Since most complex geometries are composed of primitive and distinguishable patches, each of which can be processed using a standard sub-routine. This divide-and-conquer idea will be fully employed to make the whole system flexible and feasible against an unknown part/process. Instead of a fully automatic partitioning process, which is very unlikely to be robust, we propose a semi-automatic flooding method [8] that require a manually selected seed point. Starting from this point towards its neighbors, the flooding proceeds until a process-specific criterion is broken.

3. For each surface patch, develop a generic cutter-contact (CC) curve generation algorithm that meets the specified processing requirements.

Cutter-contact curve is defined based on a scenario that the cutter is contacting the workpiece during the process. In robotic manufacturing, contactless operations such as painting usually keep the tool a proper distance away from the part for better performance. In order to validate the definition of “CC curve” for different scenarios, we employ a concept called “drive surface”, on which the CC curves reside, instead of the original surface patch.

The determination of drive surface varies with different operations, however, the fundamental requirement is to establish a mapping function from the drive domain to the original domain, such that the CC curve can be projected back to the original surface to evaluate the coverage. To simplify and unify this procedure for contact operations, a square parametric domain will be constructed by conformal mapping method [2]. Once the drive surface is identified, there is a rich body of research results (including the PC’s) in the area of CC curve generation. The most adequate CC curve strategy for the concerned process will be selected from the provided options, such as iso-planer [3], iso-parametric [2] and potential field based method [4], etc.

4. For a given CC curve, determine and optimize the robot motion based on: specified processing requirements, robotic configuration space (collision-free) and kinematic property of each joint.

The motion planning of the robot is the most challenging task of this project, which involves two technical issues, i.e. the cutter orientation planning in workpiece Cartesian space and the optimization of the joint motion in robot joint space. Pertaining to the former, the major challenge is to avoid potential interference/collision between the cutter/robotic arm and the part geometry. The PC has substantial research experience in collision avoidance of five-axis NC machining [5-7]. These algorithmic methods will facilitate the calculation of tool accessibility in a rasterized spherical region, for every CC point of the path. The inverse kinematic transformation is then to be utilized to obtain the joint coordinates for those interference-free tool orientations. Eventually, the configuration space of the robot at each CC point is identified.

By far, the candidate joint coordinates along the CC curve accumulate a large volume of raw data, which is essentially a group of 6-dimensional sites. The robotic motion planning is equal to finding an optimal path travelling through these sites, under the kinematic capacity of each joint. The research team from Googol Company has long been devoted to the robot motion control with several commercialized products [9][10][11][12][13], which establish a technical foundation to realize this objective.

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