SoftwareX 27 (2024) 101794

Contents lists available at ScienceDirect

SoftwareX

journal homepage: www.elsevier.com/locate/softx

Original Software Publication

SACETraj: An AutoCAD Catmull-Rom Spline Trajectory Interpolator

Guillaume Villeneuve, Lucas A. Hof [*]

Department of Mechanical Engineering, École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, QC, Canada, H3C 1K3

A R T I C L E I N F O

Keywords:
Toolpaths
Spline interpolation
Machining
AutoCAD
Advanced manufacturing
Motion controllers

A B S T R A C T

The presented software, programmed in C#, is a plugin for the AutoCAD computer-assisted design program that adds functionality to output toolpaths in the form of spline control points. Motion controllers are often used in laboratory settings to drive the motion of a research tool in three-dimensional space. The trajectory files accepted by these controllers are often not used in industry, for example spline interpolation, hence the tools needed to generate such files for toolpath motion are not readily available. The developed *AutoCAD Catmull-Rom Spline Trajectory Generator* aims to address this limitation and will contribute to foster intelligent manufacturing strategies at research laboratories. The generated toolpaths can either be a direct spline interpolation of drawing geometries or a derivation from it. Point density is dynamically calculated along a given path depending on user-specified tolerance. This software, adaptable to other CAD design tools, will facilitate workflow in research equipment requiring spline input of toolpaths and increase versatility of lab tools.

Metadata

Nr	Code metadata description	
C1	Current code version	1.0
C2	Permanent link to code/repository used for this code version	https://github.com/guvil-ets/SACE_Traj_Gen
C3	Permanent link to reproducible capsule	N/A
C4	Legal code license	Apache-2.0
C5	Code versioning system used	Git
C6	Software code languages, tools and services used	C# AutoCAD 2022
C7	Compilation requirements, operating environments and dependencies	To compile: ObjectARX SDK To operate: AutoCAD NETLOAD command and SACE_Traj_Gen.dll file
C8	If available, link to developer documentation/manual	https://github.com/guvil-ets/SACE_Traj_Gen
C9	Support email for questions	guillaume.villeneuve.1@ens.etsmtl.ca

1. Motivation and significance

Many areas of research involve the control of a tool or equipment's movement with positioning stages driven by a motion controller. Oftentimes, the nature of research means that the used tools and methods are not available in a complete package; researchers must develop their own equipment using commercial motion controllers. Some motion controllers, such as the Newport XPS-D Motion Controller, do not accept input trajectories in conventional Numerical Control (NC) formats for which many toolpath generation options are available, such as G-Code, but rather accept splines as trajectory inputs [1]. This forces the researcher to program a method to generate these trajectories.

Nowadays, most machines whose function is to move axes in a three-dimensional (3D) space are programmed in G-Code [2]. This workflow is almost universally adopted in industry and academia, and a multitude of paid and free software options exist to generate tool instructions in G-code, such as SolidWorks [3], Fusion360 [4], Mastercam [5], and many others. Here, 2D or 3D geometries are created or imported in the Computer-Aided Machining (CAM) software, and specific machining operations (facing, engraving, etc.) are then created and linked to the features to be machined. The typical workflow can be described by the following three (3) steps:

1. The geometry is defined, either directly in the CAM software or imported from another software.
2. Machining operations are selected from the CAM software's library and applied to elements of the geometry to machine, including options for parameters such as feed rate and depth of cut.
3. The CAM software applies post-processing steps to the set of machining operations, outputting G-Code that can be interpreted by the CNC machine's controller.

* Corresponding author at: 1100 rue Notre-Dame Ouest, Montréal, QC, Canada, H3C 1K3.
E-mail address: lucas.hof@etsmtl.ca (L.A. Hof).

https://doi.org/10.1016/j.softx.2024.101794
Received 23 February 2022; Received in revised form 16 May 2024; Accepted 12 June 2024
Available online 21 June 2024

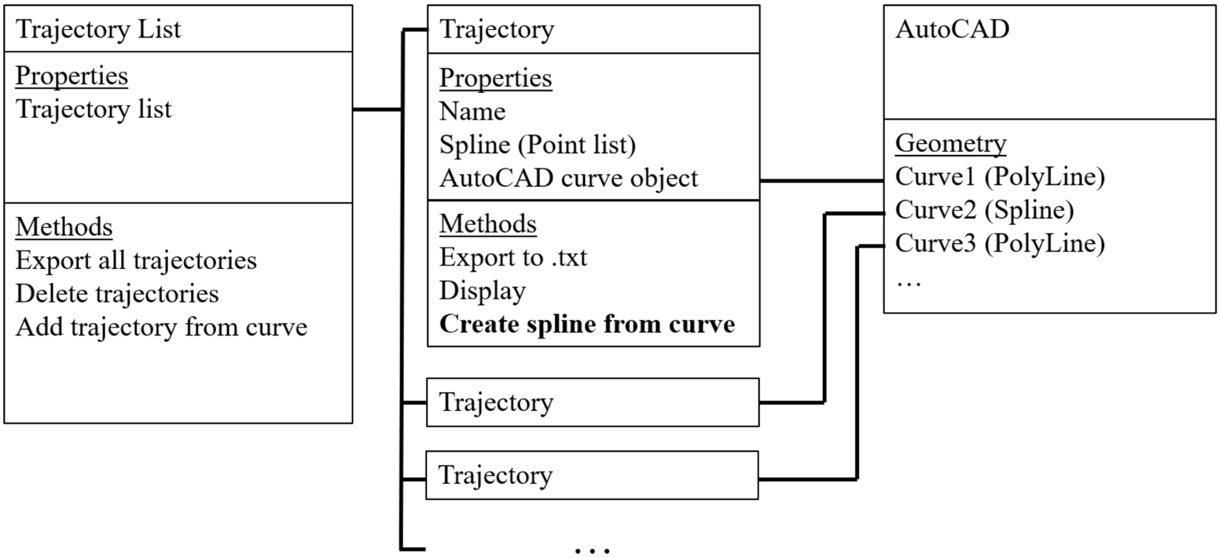

Fig. 1. Components of the program and AutoCAD integration.

However, some systems do not accept G-code, but use spline trajectories as input for toolpath generation and recent research has been done on the optimization and treatment of such spline inputs ([6,7]). Hence, there is a need to generate these splines in a cost-and-time-efficient manner. As of today, no published software is available that can complete the niche task of generating Catmull-Rom splines from Computer-Aided Design (CAD) geometries with predictable accuracy for scientific or engineering purposes.

The Catmull-Rom spline format was selected for this software as it has some key advantages over other forms of cubic splines, as well as being often used in multiple fields including the specific application this plugin was developed for. Firstly, these splines are locally defined, meaning that each control point only affects its neighborhood; changing a point will not cause instabilities in other parts of the spline [8]. Furthermore, such splines will not self-intersect in a single segment, which is an advantage in many applications [9].

The developed software addresses this issue by allowing the generation of splines directly from any AutoCAD geometry, with a user-settable interpolation error margin. This geometry can either be imported in the form of a DXF file or created and edited directly in the program. As such, this provides researchers a tool to easily obtain a spline representing their desired toolpath as input for a motion controller.

The authors aim to use this software for research in non-traditional high-precision machining methods, such as Spark-Assisted Chemical Engraving (SACE), also referred to as Electro-Chemical Discharge Machining (ECDM) ([10,11,12]), which is a manufacturing process for which no commercial solutions currently exist. It should be noted that the developed toolpath generation software could be used for any NC machining method and the SACE machining approach is used as an example of use. The developed software will be used to generate toolpaths for micro-machining of glass by SACE technology. Without the proposed software, no method was available to generate the splines necessary for such research on high-precision machining, and researchers must manually compute and program the splines one by one. The software will both save a significant amount of machining setup time and increase the capability of machining complex structures on glass. This will contribute to the development of novel applications in the field of high-precision machining, which could open new fields of research and generate novel applications.

It may be noted that the developed plugin can be used to generate control points for other types of cubic interpolating splines with good accuracy, although this is not guaranteed as it is beyond the scope of this work.

2. Software description

The developed software includes a collection of functions added to the AutoCAD interface. These functions can be called through their corresponding keywords in the command line. The functions provide different methods to generate spline toolpaths from a given drawing geometry. The generated splines are Catmull-Rom Splines with parameter $\tau = 1/2$. The geometry matrix is given in Eq. (1) [13], with p_i the control points, u the curve parameter and $p(s)$ the points along the curve. Note that this equation requires that the first and last control points of the spline are not on the curve but only serve to determine the start and end tangents.

$$p(s) = \begin{bmatrix} 1 & u & u^2 & u^3 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 1 & -\frac{5}{2} & 2 & -\frac{1}{2} \\ -\frac{1}{2} & \frac{3}{2} & -\frac{3}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} p_{i-2} \\ p_{i-1} \\ p_i \\ p_{i+1} \end{bmatrix} \quad (1)$$

Eq. (1): Catmull-Rom spline geometry matrix

2.1. Software architecture

The software's structure is composed of a Trajectory List class containing each trajectory object created by the user. These trajectory objects link to the AutoCAD Curve object associated to them, from which the spline was generated. Fig. 1 illustrates the software architecture.

The Trajectory List object contains the functions to create trajectories from curves, callable by different AutoCAD commands that will be detailed in Section 2.2. These functions create each a trajectory referencing an existing curve object. This created trajectory, upon initiation, calculates the points of the interpolated spline referencing the AutoCAD curve.

2.2. Software functionalities

The users interact with the software by using the specified AutoCAD keyword associated to the desired command, through the application command line. Firstly, they use one of the different commands that

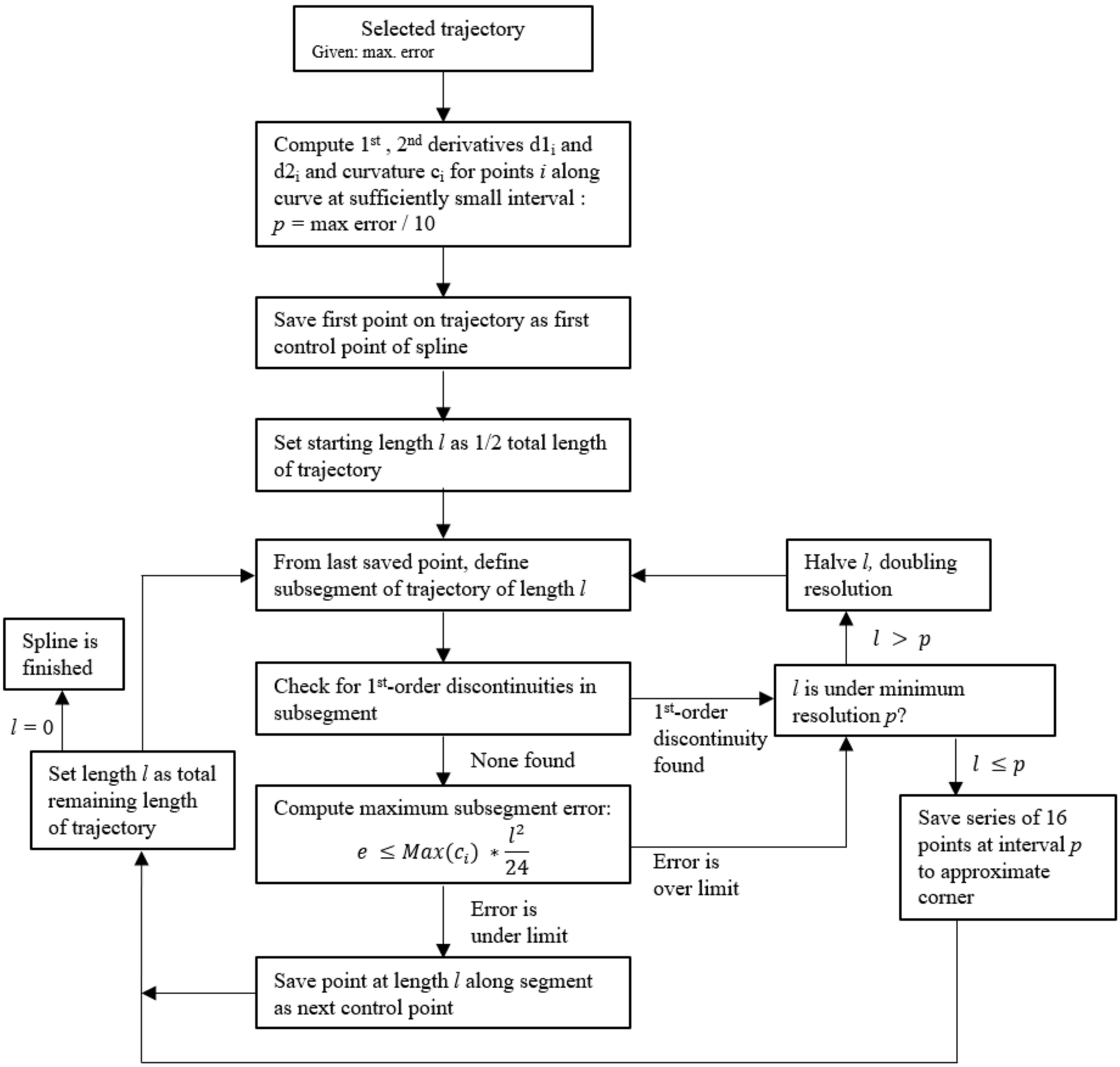

Fig. 2. Dynamic interpolation method to generate spline interpolation points from a selected curve.

create a trajectory from a curve, such as SACECONSTANTOFFSET, and then select the geometry and parameters to be used. After having created all the required trajectories with the different commands, the users will export these trajectories as text files containing the control points of each trajectory using the SACEEXPORTTRAJECTORIES command. At any point, trajectories in the list can be deleted with SACEDELETELASTTRAJECTORY or SACEDELETEALLTRAJECTORIES. Note that all functions are prefixed with SACE, allowing the user to quickly find the required function by inputting these first four letters and using the drop-down menu.

In all cases, the generated splines are within the maximum error specified by the user using SACESETMAXERROR.

The available commands to generate trajectories from a curve are the following.

- SACEPATH: Generates a single spline trajectory fitting the curve.
- SACEOFFSET: Generates a single spline trajectory at a specified offset to the curve. Parameters: offset, offset direction.
- SACEUNIFORMOFFSET: Generates a series of trajectories at uniformly decreasing offsets of the selected geometry. The last trajectory is at tool radius offset. Useful for successive machining passes. Parameters: offset step, number of passes, offset direction.

The algorithm used to generate the control points for a given trajectory is illustrated in Fig. 2. It accepts any AutoCAD curve object as input. The commands to generate different trajectory types each create a curve object and pass it to the *CurveToTraj* method, which applies the algorithm and saves the spline trajectory. In this way, expanding the software by adding new trajectory-creating commands (helical boring, etc.) only requires creating the appropriate curve object and passing it to the function *CurveToTraj*.

The algorithm begins by discretizing the curve into segments of half the maximum error, p, and calculates the first and second derivatives

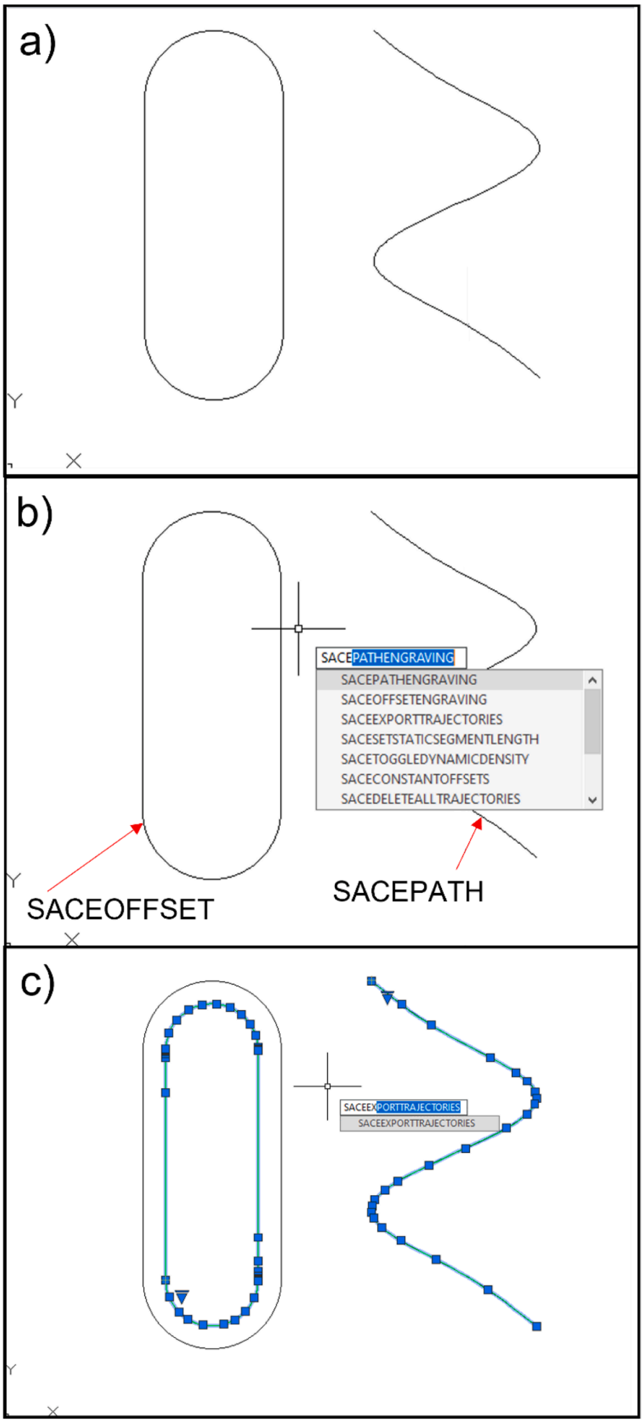

Fig. 3. Example of trajectory generation in a typical use case. In a), the initial AutoCAD geometries are shown. In b), the AutoCAD command line is used to call a plugin function to generate a tool path for each of the two geometries. In c), the resulting control points are shown and another plugin function is used to export the control points lists in text format.

and curvature for these points. This sampling density is sufficient to capture significant variations in curvature, as the error cannot be higher than half the full length of the segment between control points. Locally high curvatures between two sample points are considered first-order discontinuities and treated separately. The first point of the spline is then saved.

The next point is attempted at a length l along the curve. This length is initially approximated as half the total length of the curve. The new attempted subsegment between the initial and attempted points is checked for discontinuities by ensuring that the change in the first derivative between two sample points is always accompanied by a sufficiently high second derivative. The maximum error is then calculated by assuming the attempted segment is constantly at its maximum curvature. If these two criteria are respected, the attempted point is saved, and the remaining length of the curve is used as the next attempted length. If one of these criteria is not met, the attempted length l is halved, and a new attempted point is tried. If halving l would bring the segment length under its minimum, a series of 16 points is instead generated at the minimum length to capture any discontinuity. New points are created in this way until the end of the curve is reached.

This method (see Fig. 2) has the advantage of dynamically changing control point density and thus only having a high number of points when curvature is high. However, some CNC systems only accept splines with uniformly spaced control points or may not have the capability to maintain a constant velocity despite variable first derivatives. Therefore, a second method of spline generation was implemented and can be accessed with the SACETOGGLEDYNAMICDENSITY command. The number of evenly spaced points is calculated from the maximum segment length set with the SACESETSTATICSEGMENTLENGTH command. This second method also has a much faster computation speed as no calculations are necessary.

2.3. Error analysis

The generated splines are within the maximum error as specified by the user with SACESETMAXERROR. The maximum error can be calculated as a function of the maximum second derivative and segment length [14] and the equation adapted to cubic splines is presented in Eq. (2); f being the approximated curve, s the spline and l the segment length between the two control points. The expression $sup \parallel f - s \parallel_{seg}$ represents the maximum interpolation error on the segment.

$$sup \parallel f - s \parallel_{seg} = f^{(2)}_{\max,\ seg} \frac{l^2}{24} \tag{2}$$

Eq. (2): Maximum interpolation error

Catmull-Rom splines being a class of cubic splines, this relation guarantees a maximum bound on the deviation of the generated spline with respect to the original AutoCAD geometry. As presented in Section 2.2, the maximum length l of each segment is calculated as a function of the maximum second derivative. Hence, the interpolation error's upper bound is mathematically guaranteed to meet the user's specified settings.

3. Illustrative examples

3.1. Typical use case

The case study example in Fig. 3 shows the workflow for creating and exporting trajectories. Beginning with AutoCAD line, polyline, or spline geometries (Fig. 3.a), the user calls functions using the command line to generate the required toolpaths (Fig. 3.b). All callable functions have the prefix SACE, so the user can easily find a list of available commands by typing SACE in the command line and browsing the drop-down list. In the example, SACEOFFSET is used on the left feature to generate a path at a fixed offset from the source geometry, the user being prompted to specify geometry, offset value and direction when the command is called. The SACEPATH command is used to generate a tool path directly on the remaining feature. Finally, the SACEEXPORTTRAJECTORIES command allows the user to save the generated trajectories as .txt files, opening the built-in Windows Explorer interface to do so (Fig. 3.c.).

3.1. Processing time

A sample geometry, shown in Fig. 4a), was created in AutoCAD using

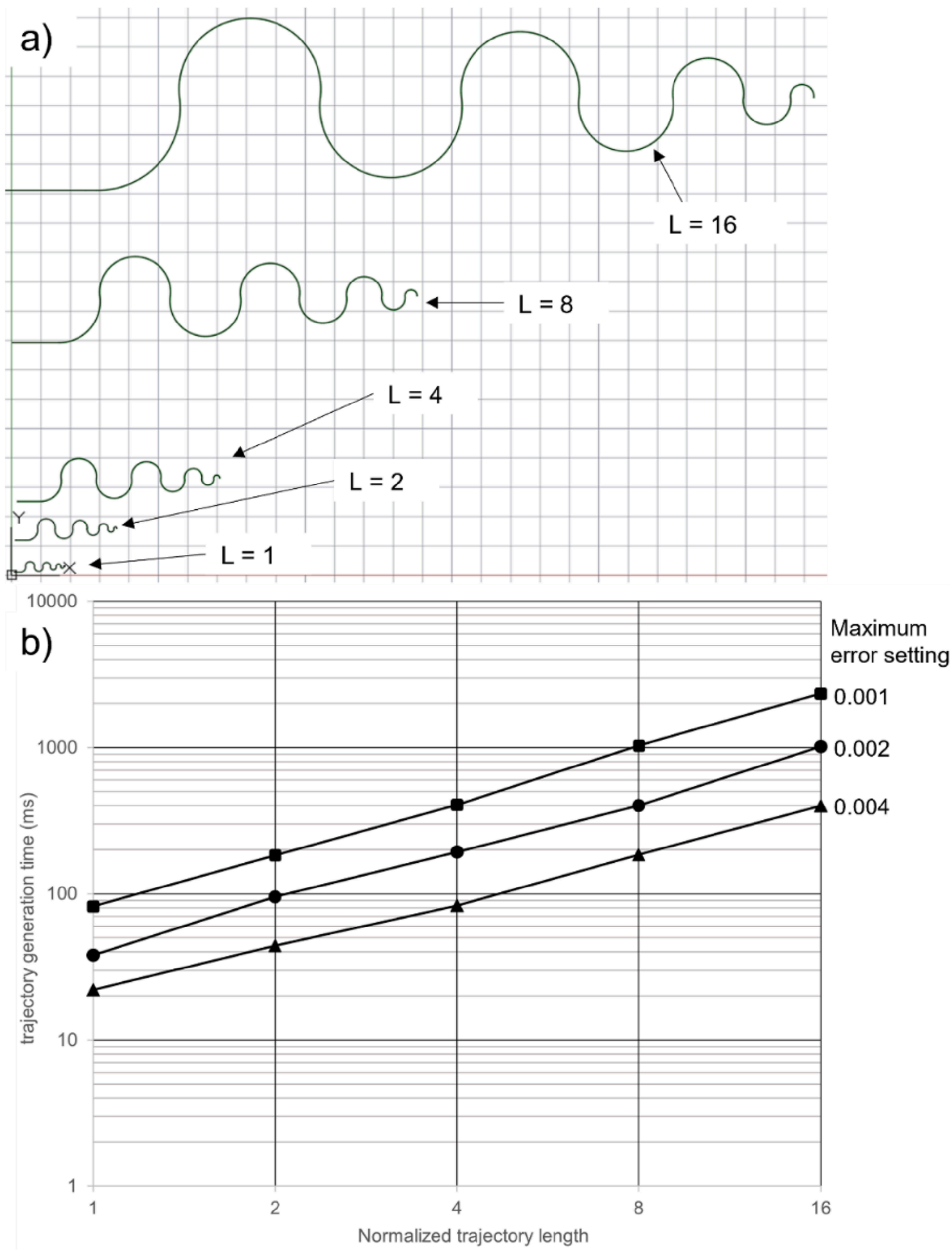

Fig. 4. Performance test; a) test trajectory at varying scales; b) trajectory generation time by specified maximum error against the normalized trajectory length. Trajectory length is provided in multiples of 28 units, the length of the shortest trajectory.

the polyline tool. Copies were then created at increasing scales, ranging from 1 (the original geometry) to 16. The lengths of the geometry are normalized to multiples of the length of the smallest geometry (here, 28 units).

A trajectory was then generated for each line with the SACEPATH command. This was repeated for a maximum error of 0.001, 0.002 and 0.004, respectively, with the SACESETMAXERROR command.

Fig. 4b) shows the processing time in milliseconds for each trajectory length and error level. Note the linear relation between maximum error setting and processing time, as well as between trajectory length and processing time. This means that calculation time will be proportional to the length of the selected geometry in all cases.

4. Impact

This software allows the use of 2.5D motion controllers that accept spline inputs at their full potential. Motion controllers are often needed in any research and development environment for positioning and machining applications. Almost every CAD tool allows exporting of geometry as DXF files, and AutoCAD can be acquired for free in an educational version. Hence, any student or researcher can generate spline toolpaths from geometry of any complexity with a low entry-barrier. In the past, the generation of such splines and extraction of their control points would be a lengthy process, especially for complex geometry requiring many separate trajectories.

Current developments in industry and research focus on creating a cost-and-time efficient workflow from part design to the manufacturing process [15]. These advancements are grouped into what is now called Industry 4.0. It is characterized by the demand for mass-personalization, where the programming of toolpaths for individual (batch size 1) parts is also a significant part of labor and costs [16]. Flexibility of manufacturing systems is a key point in the current industrial landscape

[17]. This software and its derivatives can be used to reduce the time needed to prepare the machining of a product. Particularly, the developed toolpath generation software contributes to this Industry 4.0 manufacturing trend, specifically for prototyping in research where programming of toolpaths represents a larger share of time expenditure. Motion controllers accepting spline input are used in diverse fields of research and are applicable to many different operations, such as precision machining, laser engraving [18], and additive manufacturing [19] among others.

At the time of writing this article, this software has been used to generate toolpaths for a Spark-Assisted Chemical Engraving (SACE) research machine. SACE is generally used to machine non-conductive hard-to-machine materials at dimensions around 100 μm. Its most notable applications are in Micro-Electromechanical systems (MEMS) and microfluidics [7]. Until now, SACE machining toolpaths by some researchers were either painstakingly manually programmed or limited to simple lines and arcs [10]. Now, arbitrarily complex shapes can be made into toolpaths with little resource investment, enhancing the development of novel applications in this field.

5. Conclusions

A plugin for AutoCAD allowing the generation of Catmull-Rom spline trajectories from drawing geometry was presented and its program structure was detailed. The developed functions were presented and explained and example use cases were demonstrated. An algorithm for dynamically spaced spline interpolation was introduced, allowing for a lower number of control points and faster treatment.

This plugin will be of use to many researchers using motion controllers that rely on spline input, saving them precious time and it will ensure that their trajectories correctly match their original geometry at the required precision. Variable spline segment length helps to reduce program file size. The context of this software within current industrial and research developments (e.g. Industry 4.0 manufacturing approaches) was presented.

Future improvements for the developed software may include:

- Support for other machining trajectories, such as pockets, surfaces and helical boring
- Support for types of trajectories other than Catmull-Rom splines (PVT, other types of splines),
- An improved user interface, including editing of all current trajectories.

CRediT authorship contribution statement

Guillaume Villeneuve: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Lucas A. Hof:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) under the Discovery Grant (RGPIN-2019-05973).

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