CAD Framework for Parametric Design of V-Groove-Based Functional Surfaces

Jonas T. Churchill-Baird[1], O. Remus Tutunea-Fatan[2] and Evgueni V. Bordatchev[3]

[1]Western University, jchurc4@uwo.ca
[2]Western University, rtutunea@eng.uwo.ca
[3]National Research Council of Canada, evgueni.bordatchev@nrc-cnrc.gc.ca

Corresponding authors: O. Remus Tutunea-Fatan, rtutunea@eng.uwo.ca
Evgueni Bordatchev, evgueni.bordatchev@nrc-cnrc.gc.ca

Abstract. This study proposes an integrated approach for the parametric design and fabrication of functional surfaces formed by V-grooves as trilateral geometric features. The primary rationale of the present study resides in the fact that there are no CAD/CAM solutions available for the automated generation of the variety of geometrical designs and tool path trajectories that are specifically developed for micromachining of V-grooves by an ultraprecise single point cutting process. To address this, the focus of the current study is mainly on the development of an integrated CAD framework to be used for the parametric design and fabrication of linear V-groove-based functional surfaces. The proposed framework implements on parametric design of linear V-grooves only and consists of three main function blocks (MFB) defining core operations and six secondary function blocks (SFB) that are responsible for defining the required design and process parameters. The three MFBs are "Parametric Model" (MFB1), "Solid Modeler" (MFB2), and "NC Postprocessor" (MFB3). The proposed integrated design and fabrication approach enables high precision fabrication of micro/nano-scale functional surfaces based on complex configurations of linear V-grooves for a broad variety of applications.

Keywords: CAD Framework, Functional Surfaces, V-Grooves, Parametric Design, Solid Modelling
DOI: https://doi.org/10.14733/cadaps.2022.1109-1116

1 INTRODUCTION

Functional surfaces are patterned/structured surfaces tailored to a specific surface engineering application, such as the control of wettability, friction, aero- and hydro-dynamics, etc. Different applications require different micro-/nano-scale geometric structures and features that are responsible for a specific functionality. Micro-grooves – alternatively termed as micro-riblets - are one of the most versatile structures capable to provide functionality for different applications. There are many examples of these types of surfaces that can be found in nature serving as functional prototypes and designs for bio-inspired drag-reduction surfaces [1, 2]. Other common applications of functional surfaces that use V-grooves as their design element include open-channel microfluidics [10], friction control [8], micro Fresnel lenses [9], sun light guiding and trapping [4] and automotive [3] optical designs. For the open-channel microfluidics, capillary forces cause flow through micro-channels, allowing low-cost and low-volume diagnostic devices to be created [10]. V-grooves provide friction control by allowing lubricant to flow freely along micro-channels found upon a stochastic surface, allowing for full lubrication on a surface and improvement of the tribological conditions of sheet forming processes [8]. Low-cost V-groove-based sun light trapping structures placed on top of solar panels improve photo-voltaic energy conversion of >10% [4]. Novel sine-shape V-grooves can be efficiently used in automotive light guides reaching an illumination efficiency of 97.7% [3].

However, the high-quality cost-efficient micro-fabrication of high-precision micro-/nano-scale V-grooves is not a trivial manufacturing task especially for ferrous alloy-based tooling surfaces. The main technical challenge in the microfabrication of V-grooves consists in the achievement of high surface quality (e.g., Sa < 10 nm) and precise and burr-less form geometry that are critically required for the desired optical performance. Single point diamond cutting is a common machining method involved in the fabrication of micro V-grooves in non-ferrous materials [5]. This technology usually involves up to 6-axis motion control for high-precision micro-cutting on free-form surfaces [7]. When using this technology, a V-groove is generated as a geometric copy of the shape of the single-point cutting tool. Several different cutting strategies can be used for this purpose [9], to avoid bending and breakage of high aspect ratio riblets and pyramids that are typically used in super-hydrophobic surfaces [1]. Strategies that are different than simultaneous two-flank axial cutting – such as alternating/one-flank cutting - are required in order to fabricate high-aspect ratio V-grooves with included angles as low as 15 degrees. Available strategy variants include those relying on a constant chip thickness or a constant cutting force [6]. Nonetheless, similar structures can be generated by redistributing a superficial layer of molten material that was brought to this state by means of laser irradiation. This represents a relatively new alternative to micro-cutting technology that can be used towards the fabrication of functional micro V-grooves, structures and surfaces [3].

The main driver of the current study is represented by the fact that there are no available CAD/CAM solutions and/or software options that can be used for tool path generation, process planning or fabrication strategies associated with single and/or a set of linearly and spatially oriented V-grooves. To consolidate the global strategy and methodology of the proposed CAD solution, this work will be mainly focused on the development of a CAD framework to be used during parametric design and post-processing of linear V-groove-based functional surfaces tailored towards primarily (but without being limited to) aero/hydro-dynamic drag reduction applications. The proposed CAD framework is comprised of several functional blocks that include: i) parametric model of a rectangular workpiece, ii) parametric model of a single V-groove, iii) parametric model of a flat functional surface as a set of periodically placed V-grooves, iv) cutting tool geometry and its parameters, cutting process strategy, and v) cutting process plan. These functional blocks enable the automatic generation of a solid geometric model of the V-groove-based functional surface as well as that of an NC code to be used to fabricate the desired structured surface.

2 GENERALIZED CAD FRAMEWORK

The effective development of functional surfaces requires several interconnected steps starting with the input of design parameters and the modeling of the surface followed by its fabrication. Once the first surface prototypes will be fabricated, they could be subjected to physical tests for the evaluation of their functional performance.

According to this intention, the proposed framework depicted in Fig. 1 consists of several functional blocks. Each function block (FB) represents a specific operation or a set of the geometric parameters required to define a particular design component. In addition, the links between FBs depict the informational flow required to obtain one of the two intended outputs of the framework: geometric model and NC program.

The CAD framework consists of three main function blocks (MFB) defining core operations and six secondary function blocks (SFB) responsible for defining required design and process parameters. The three MFBs are "Parametric Model" (MFB1), "CAD Module" (MFB2), and "CAM Module" (MFB3). The main function of the MFB1 is to define the parametric model of the desired functional surface. For this purpose, this block relies on a set of trigonometric equations to describe the geometry of the functional surface. MFB2 transforms these equations into a corresponding solid model that can be used for visualization, numerical simulations and many other purposes. Finally, MFB3 is used to generate the NC program used in multi-axis SPDC operations. This last FB is the most complex one since it requires comprehensive information with all prior design and fabricated phases.

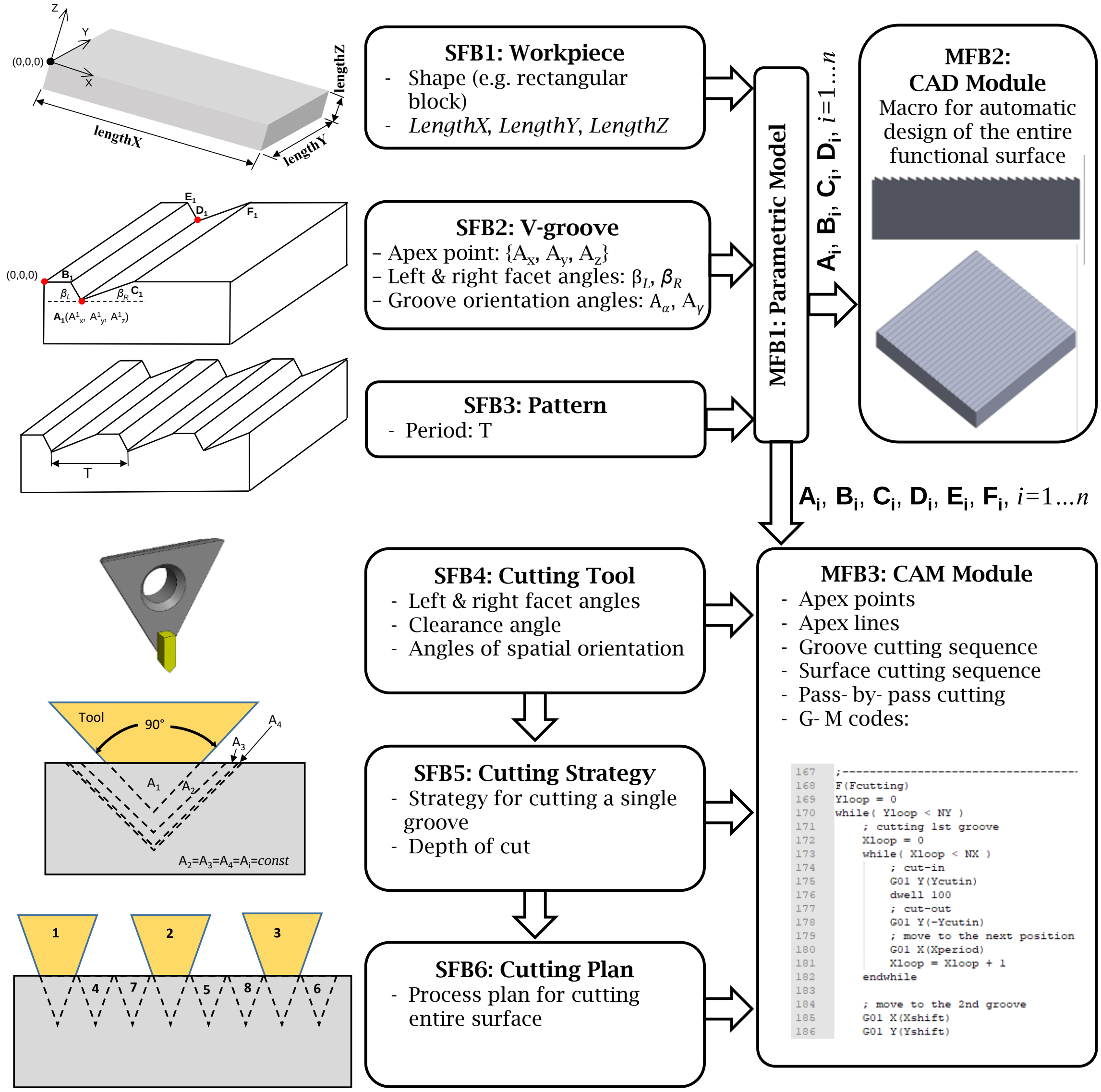

Figure 1: Generalized CAD/CAM Framework.

3 PARAMETRIC MODEL OF THE FUNCTIONAL SURFACE (MFB1)

From a general point of view, the design of any V-groove-based functional surface is comprised of three main geometric components: stock surface geometry, single groove geometry, and distribution pattern of the V-grooves. For this reason, the parametric model of the functional surface design can be conceived as a set of interconnected trigonometric equations involving the aforementioned geometric components.

3.1 Workpiece (SFB1)

This functional block constitutes the baseline for all SFB's and SBF1 requires some basic input to define the overall dimensions of the workpiece stock (Fig. 2). The workpiece origin is also defined in this particular SFB such that all other geometric parameters will become dependent on its location. While more complex stock geometries could also be imagined and used, the current study will assume a simple rectangular shape.

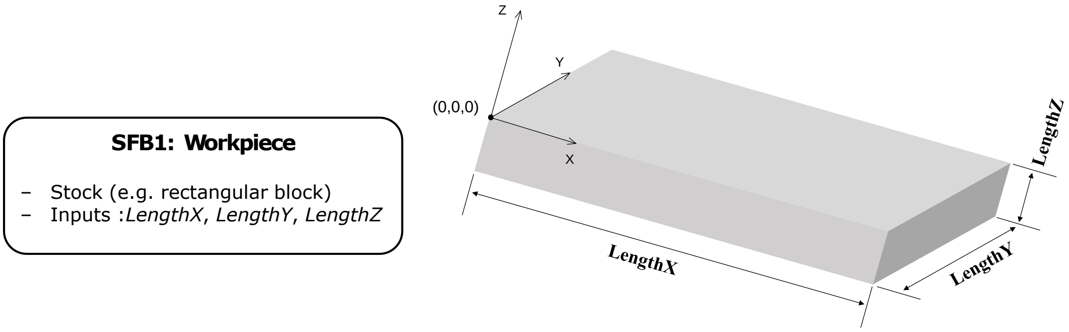

Figure 2: Stock geometry and geometric parameters.

One of the connections between this particular SFB and the next ones is accomplished through stock width ($LengthY$), especially since this input parameter is involved in the definition of the apex line (Fig. 3). In addition to the width, stock length ($LengthX$) is also connected to SFB3 since it affects the total number of V-grooves to be generated on the surface:

$$Grooves_{total} = \frac{LengthX}{T} . \tag{3.1}$$

3.2 V-Groove (SFB2)

This constitutes the most important functional blocks of the proposed framework since it encompasses the definition of the unit V-groove to be subsequently multiplied into an array. Figure 3 shows the seven input parameters required to fully define/constrain the geometry of the unit groove. The input parameters include: coordinates of the front apex point A ($\mathbf{A}_1 = A_X^1, A_Y^1, A_Z^1$), left and right facet angles (β_L , β_R), and two groove orientation angles around X and Z axes (A_α , A_γ). This definition of the unit groove enables full control of its geometry to be independent from that of the array.

Once the front apex point $\mathbf{A}_1$ is defined, the rear apex point can be determined through a succession of rotations about Z and Y axes (assume $x_D = LengthY$) according to:

$$\frac{x_D - x_A}{a} = \frac{y_D - y_A}{b} = \frac{z_D - z_A}{c} \tag{3.2}$$

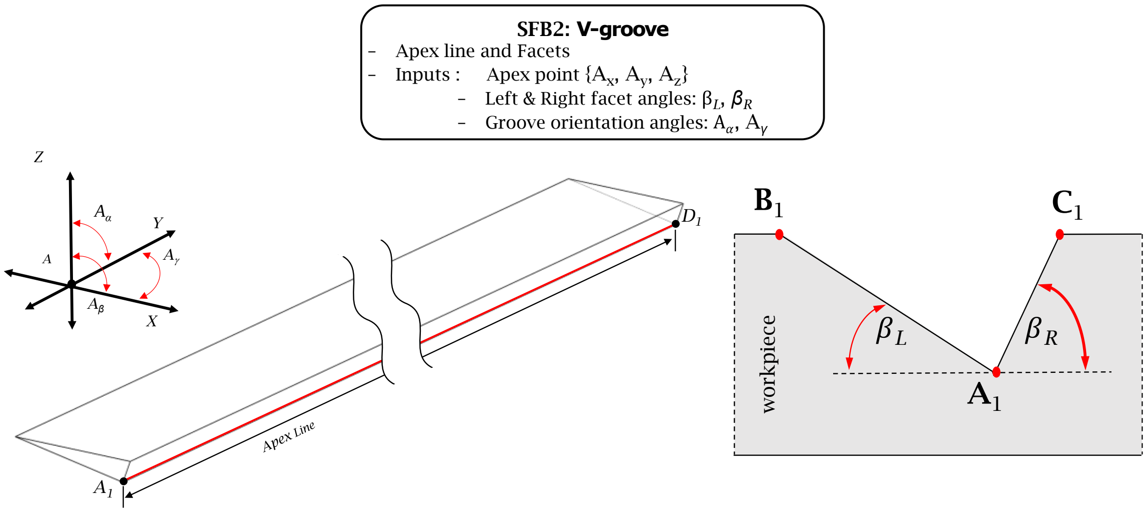

Figure 3: Geometric definition of the unit V-groove.

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \mathbf{R}_x \cdot \mathbf{R}_z \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \tag{3.3}$$

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(A_\alpha) & -\sin(A_\alpha) \\ 0 & \sin(A_\alpha) & \cos(A_\alpha) \end{pmatrix} \cdot \begin{pmatrix} \cos(A_\gamma) & -\sin(A_\gamma) & 0 \\ \sin(A_\gamma) & \cos(A_\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \tag{3.4}$$

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} \cos(A_\gamma) \\ \cos(A_\alpha)\sin(A_\gamma) \\ \sin(A_\alpha)\sin(A_\gamma) \end{pmatrix} \tag{3.5}$$

Once the bottom V-groove line - referred to as the apex line - is determined, the next steps are to define the vertices associated with left and right facets (B_1 and C_1). This operation involves β_L and β_R angles and procedures similar to those shown in Eq's. 3.2-3.5 in order to uniquely determine the location of both front and rear vertices on the lateral facets of the V-groove.

3.3 Pattern (SFB3)

The third functional block defines the array pattern of the functional surface. The only input parameter for this SFB is represented by the period of the V-grooves (T) defined as the distance between two consecutive apices (Fig. 4) measured along the X axis. According to this definition of the period, the functional surface will consist of n evenly spaced V-grooves that are located along $LengthX$.

Taken together, SFB 1-3 are integrated in MFB1 that outputs two sets of data: i) $\mathrm{A}_i, \mathrm{B}_1, \mathrm{C}_1, \mathrm{D}_1, i = 1 \ldots n$, to become an input to MFB2 (responsible for the generation of a geometric model of the functional surface), and ii) $\mathrm{A}_i, \mathrm{B}_1, \mathrm{C}_1, \mathrm{D}_1, \mathrm{E}_1, \mathrm{F}_1, i = 1 \ldots n$ to become an input to MFB3 (responsible for generation of the NC program to be used during fabrication of the functional surface). These three SFBs form the most important part of the developed CAD framework.

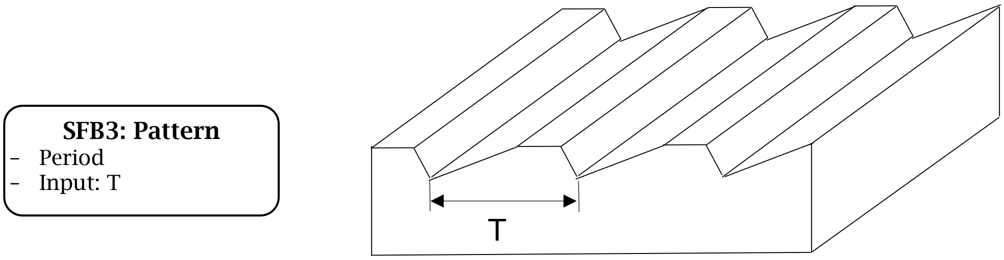

Figure 4: Definition of the V-groove period.

4 AUTOMATED GENERATION OF THE GEOMETRIC MODEL (MFB2)

The developed CAD macro/module constitutes the core of MFB2. This module is comprised of three steps: stock/blank generation, unit V-groove generation followed by the multiplication of the unit V-groove into an array to cover the entire top surface of the blank (Fig. 5).

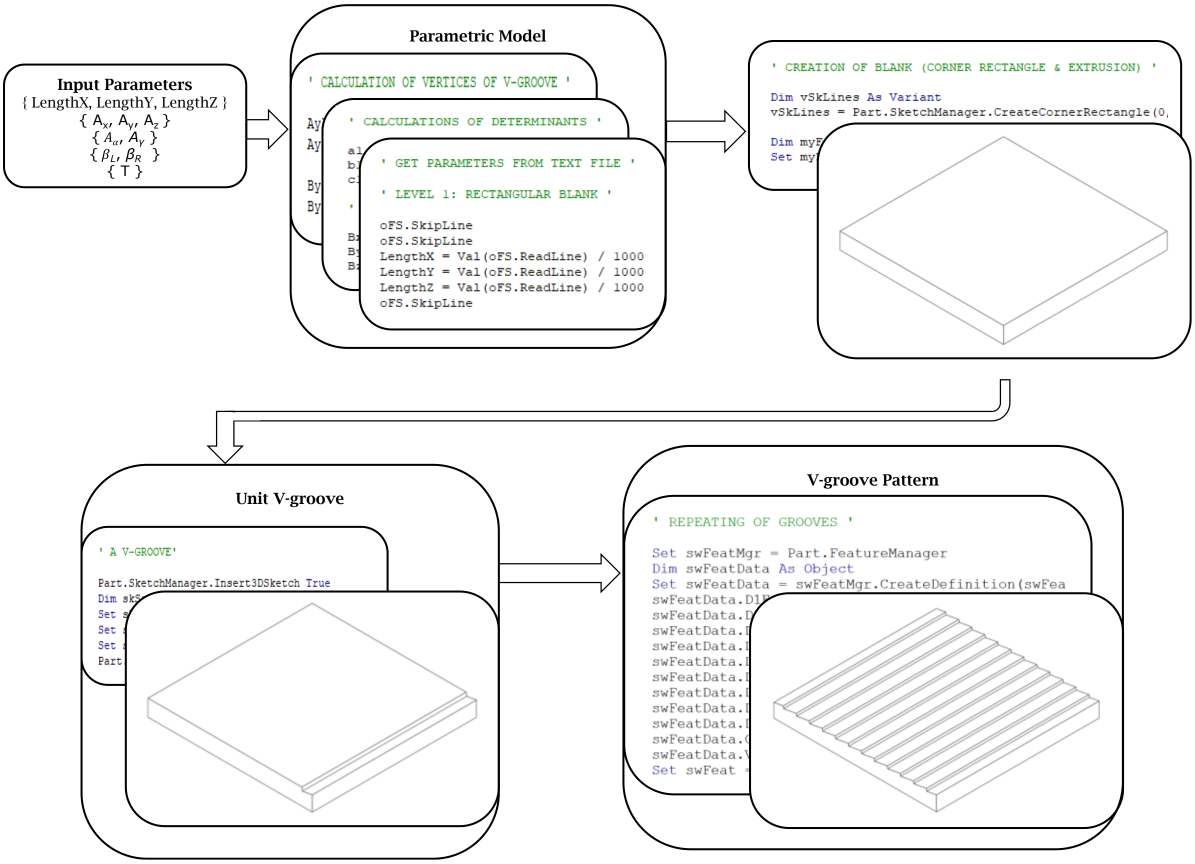

Figure 5: Information flow in MBF2.

To generate the single/unit V-groove, a lofted-cut operation is performed between the front and rear sketches defined by the three vertices as determined by the MBF2 module ($\{A_1, B_1, C_1\}$ and $\{D_1, E_1, F_1\}$). Evidently, the final design of the structured surface will be fully controlled by the aforementioned seven geometric input parameters.

The modeling approach selected for the array of V-grooves enables a broad range of "degrees of freedom" in terms of design and Fig. 6 illustrates just several such possibilities. While some of these design DOFs/geometric parameters are more intuitive than others, the complete 3D model will undoubtedly clarify the final shape of the functional surface. While the values used generate the sample geometries illustrated in Fig. 6 can be regarded as unitless, their actual scale can vary anywhere between millimeters and nanometers. Similar to any other commercial CAD software, the module cannot accurately handle dimensions that are different by more than three orders of magnitude, such that alternate approaches – typically involving partial representations of the structured array – are required in this case.

With respect to their practical implications, the location of the front apex is clearly correlated with the starting depth of the groove. Nonetheless, as A_α could also deviate from its null values, variable groove depths could also be accounted for by the proposed framework. Of note, the axial cross section of these V-grooves will no longer be constant. On the other hand, continuous variations of the other orientation angle (A_γ) could account for nonlinear V-groove geometries, such as the case of sinusoidal grooves, for instance.

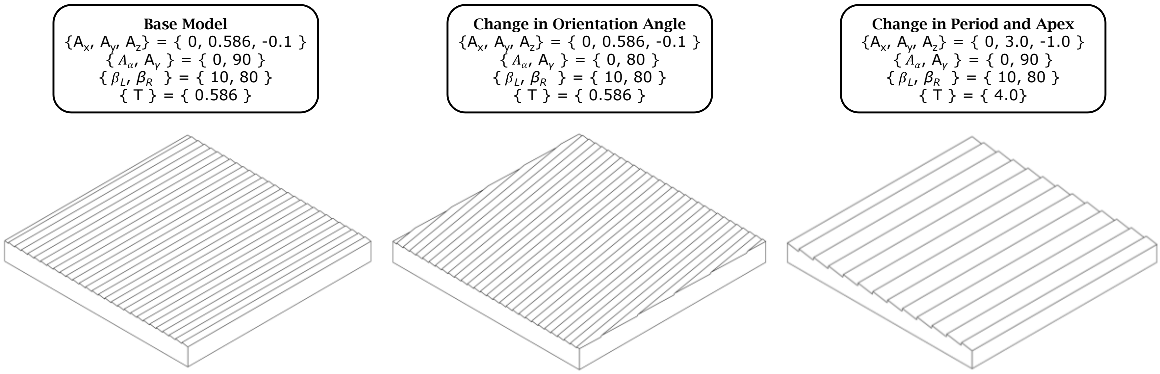

Figure 6: Samples of framework functionality (units in mm's).

5 CAM MODULE (MFB3)

The geometric model of the V-groove-based functional surface represents the key input to the fabrication module aiming to produce its physical replica. Because of this, the CAM module represents one of the key components of the developed framework since in addition to the geometric information it also requires details on tool geometry (SFB4), cutting strategy (SFB5), as well as the overall machining plan for the entire surface (SFB6). Unlike the vast majority of the conventional CAM software, the current module does not include geometry visualization capabilities since they are one of the core components of MFB2. The primary output of MBF3 is represented by the NC code to be used to machine the intended array of microstructures.

6 SUMMARY AND CONCLUSIONS

This study was focused on the development of a CAD framework for parametric design and post-processing of the V-groove-based functional surfaces. The framework takes input in the form of seven geometric parameters and generates a solid model of the desired structured surface. Future extensions of this work will focus on the integration of a CAM module to generate the NC code to constitute the basis of the micromachining operation. The physical prototype to be fabricated in this manner could be then tested over the medium to long term in broad variety of applications where as immediate interests exist in the area of fouling resistant surfaces.

7 ACKNOWLEDGMENTS

The work presented in this study is the result of the collaboration between Western University (London, Ontario, Canada) and National Research Council of Canada (London, Ontario, Canada). Partial financial support was also provided by Natural Sciences and Engineering Research Council (NSERC) of Canada. The authors have made equal contributions to this manuscript.

8 REFERENCES

[1] Abdulbari, H.A.; Mahammed, H.D.; Hassan, Z.B.Y.: Bio-inspired passive drag reduction techniques: A review: ChemBioEng Reviews, 2(3), 2015, 185-203. https://doi.org/10.1002/cben.201400033
[2] Bixler, G. D.; Bhushan, B.: Bioinspired micro/nanostructured surfaces for oil drag reduction in closed channel flow: Soft Matter, 9(5), 2013, 1620-1635. https://doi.org/10.1039/c2sm27070f
[3] Bordatchev, E.V.; Küpper, M.; Cvijanovic, S.J.; Willenborg, E.; Milliken, N.; Temmler, A.; Tutunea-Fatan, O.R.: Edge-lit sine-shape wedged light guides: Design, optical simulation, laser-remelting-based precision fabrication, and optical performance evaluation, Precision Engineering, 66, 2020, 333-346. https://doi.org/10.1016/j.precisioneng.2020.07.004
[4] Bordatchev, E.; Tauhiduzzaman, M.; Dey, R.: Enhancement of photovoltaic cell performance using periodic triangular gratings: Journal of Photonics for Energy, 4(1), 2014, 044599; https://doi.org/10.1117/1.jpe.4.044599
[5] Brinksmeier, E.; Gläbe, R.; Schönemann, L.: Review on diamond-machining processes for the generation of functional surface structures, CIRP Journal of Manufacturing Science and Technology, 5(1), 2012, 1-7. https://doi.org/10.1016/j.cirpj.2011.10.003
[6] Joao, D.; Milliken, N.; Tutunea-Fatan, O.R.; Bordatchev, E.V.: Axial strategies for ultraprecise single point cutting of V-grooves, Precision Engineering, 66, 2020, 10-20. https://doi.org/10.1016/j.precisioneng.2020.06.004
[7] Moriya, T.; Nakamoto, K.; Ishida, T.; Takeuchi, Y.: Creation of V-shaped microgrooves with flat-ends by 6-axis control ultraprecision machining, CIRP Annals - Manufacturing Technology, 59(1), 2010, 61-66. https://doi.org/10.1016/j.cirp.2010.03.054
[8] Steinhoff, K.; Rasp, W.; Pawelski, O.: Development of deterministic-stochastic surface structures to improve the tribological conditions of sheet forming processes, Journal of Materials Processing Technology, 60, 1996, 355-361. https://doi.org/10.1016/0924-0136(96)02354-0
[9] Takeuchi, Y.; Maeda, S.; Kawai, T.; Sawada, K.: Manufacture of Multiple-focus Micro Fresnel Lenses by Means of Nonrotational Diamond Grooving, CIRP Annals - Manufacturing Technology, 51(1), 2002, 343-346. https://doi.org/10.1016/s0007-8506(07)61532-7
[10] Tian, J.; Kannangara, D.; Li, X.; Shen, W.: Capillary driven low-cost V-groove microfluidic device with high sample transport efficiency, Lab Chip, 2010, 10(17), 2258-2264. https://doi.org/10.1039/c003728a