Title:
STEP-compliant Data Exchange of T-spline Models between CAx Systems

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Introduction:
T-spline is a new approach for defining freeform surface with relatively less control points than NURBS and is able to represent a model using a single surface without joining errors. Whereas, the complexity of T-spline data models leads great difficulties to its programming, which hinders the research and development of T-spline technologies. In addition, the data exchange format of T-spline models still remains on a primitive level, and no standards has been published so far. This article gives a reconsideration to the existing T-spline definition, and proposes a set of redesigned data models which have much more understanding conveniences to both human and computer. Moreover, the STEP-compliant data models are designed using the proposed T-spline models, so as to standardize their data exchange between different CAx systems. The combination of T-spline with other product models in ISO 10303 makes it feasible to exchange the versatile resource data in a hybrid neutral file. A prototype system is developed for the validation purpose, which consists of a TSM-to-STEP converter, a STEP parser and a T-spline kernel. Using the developed prototype system, one can automatically convert a TSM file exported from the Rhino system to a STEP file in P21 format, which can be then parsed using the STEP parser and processed in the T-spline kernel. Some testing examples shows that the proposed data models are much more efficient in processing and exchanging the T-spline data.

Main Idea:
T-spline has attracted great interests from researchers since its emergency in 2003 [10]. Comparing to NURBS, it has great advantages of less control points and localized refinement and tessellation operations [9]. In addition, T-spline has shown its progressively powerful modeling functions comparing to NURBS, especially after Rhino releases the T-spline plug-in [1]. Although T-spline has successfully attracted a lot of researcher interests in the last decade, there is still lack of commercial softwares package supporting T-spline modelling and data exchange functionalities inside their cores. The success of T-spline kernel in Rhino has shown an optimistic prospect on integrating T-spline into other CAx systems. For example, a CAD system can provide users another modelling method via the T-spline, a CAM system may support a novel path planning ability to generate a five-axis machining path for a whole part directly [1], and a CNC system could use a T-spline model as its precisely defined workpiece part for object-oriented and inspection based on closed-loop manufacturing [2], which as well obeys the concept of STEP-CNC [6][11]. Since the geometric data models are the base for other applications, the addition of T-spline extends and changes the way of many other STEP-compliant CAx applications as well. It is urgent to exchange T-spline models between different CAx systems, which is just as the requisite from conventional B-Rep models. In order to fulfill this request, Rhino has recently unfolded a text-based TSM (T-spline Mesh) file format for storing its exported T-spline data.

However, the practical use has proved that the analyticity is far from satisfied for complex data exchange. Developers generally have to spend a lot of time and effort in developing a data parser, provided they want to import a T-spline model generated by Rhino. In order to avoid this dilemma, the standardization of T-spline models becomes exigent before miscellaneous specified definitions flood the research and development fields. The definitions of T-spline models must be compact for storing, flexible for data defining, and reversible for indexing.

Drawbacks in the existing T-mesh definitions

The definition of T-spline reluctantly works for the theoretical description [9], whereas brings a lot of troubles in theory understanding, data exchanging and program developing. Most researchers have defined T-spline surface by means of a control grid called T-mesh [9][7][8][9], which provides information both in the cartesian and parametric spaces. These definitions are basically extended from the tensor-product B-spline surface, which use a rectangular grid of control points in the blending equation. In order to describe the parametric space, the pre-image of a T-mesh is introduced as an attachment to the T-mesh. In spite of their popularity, there are essentially three major drawbacks in these T-spline definitions:

- A T-mesh contains not only cartesian but also parametric data, which brings great complexities in data managing and algorithms developing.
- The complexity of the pre-image of a T-mesh is ignored significantly, although it contains the most abundant data like vertices, edges and faces.
- Most current researches and applications are focusing on the T-spline of degree three. However, in case of even degrees, the current principles of T-mesh may face a risk of expiration.

The main reason of the aforementioned drawbacks is because of the lack of comprehensively designed T-spline data models. For this reason, there is still no standardized T-spline file format for its data exchange. Consequently, this paper reconsiders the definition of T-spline models, so as to obtain the human and computer friendly models for the data exchange between different CAx systems.

New data models of T-spline

In the paper, we propose three layers of data models for the T-spline surface representation, which stand for the parametric, topological and cartesian aspects respectively. The new T-spline data models reflect the significant single-responsibility principle in terms of software engineering. Each layer of data models holds relatively consistent and stable data structures, and persists homogeneous functionalities. As the new T-spline data models that fall into each layer form three typical graph individually, the graph analyzing methods [5] would be possibly introduced to support the T-spline theories. Amount of algorithms of graph theory would be integrated in the T-spline applications like subdivision. Fig. 1 gives an example of the three-layer T-spline data models.

- Parametric Layer: T-image: A T-image contains the parametrically drawable data models on the parametric layer. This layer considers no knot multiplicities, as they cannot be clearly “drawn” in the parametric space. A T-image consists of a set of T-faces, which is constituted by a loop of T-links. A T-link is in fact an oriented edge, which refers a T-edge and specifies an orientation. A T-edge is determined by a start T-vertex and an end T-vertex, while a T-vertex contains a parametric coordinate (s, t) and four T-link pointers to its adjacent “north”, “west”, “south” and “east” T-links.
- Topological Layer: T-connect: A T-connect contains the data models on the topological layer. It plays the role of a bridge between the parametric and cartesian layers. It focuses specially on the topological connection between T-nodes, thus can easily solve the knot multiplicity problem during the deduction of knot vectors. A T-connect possesses a set of T-nodes, which have a T-vertex, T-link, or T-face pointer (according to the degree parities in s and t directions) and a T-point pointer for indexing data models between multiple layers. Meanwhile, it also holds four T-node pointers to its “north”, “west”, “south” and “east” neighbors for the use of knot vector deduction.
- Cartesian Layer: T-pointset: A T-pointset contains the data models on the cartesian layer. This layer covers the geometric data of a T-mesh. A T-pointset groups a set of T-points that are

also called rational points, since they provides not only (x, y, z) coordinates but also point-based weights. Generally, T-points can be mapped one-to-one to T-nodes.

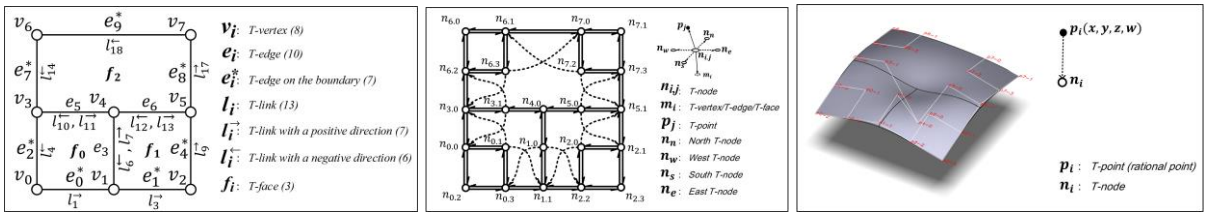

Fig. 1: The three-layer T-spline data models: (a) parametric layer T-image, (b) topological layer T-connect, (c) cartesian layer T-pointset.

STEP-compliant T-spline data models

This section implements the new T-spline data models using the EXPRESS language [3], which can inherently merge the object-oriented architecture into the T-spline data structures. The new defined T-spline models are embedded into the AP238 standard (STEP-NC AIM) [4], in which a lot of modeling work can be saved by using inheritances and compositions of the abundant existing entities. Amount of EXPRESS-G diagrams are illustrated to present the hierarchical structures. According to the previous definitions, the STEP-compliant data models are separated into three groups: the parametric, topological and cartesian models.

- Parametric models: The parametric models includes the entities *t_image*, *t_vertex*, *t_edge*, *t_link*, *t_face*, *t_edge_condition*, etc. The entity *t_vertex* represents the model of a T-vertex, the entity *t_edge* stands for a T-edge, and others are obviously understood in a similar way. Fig. 2 shows the EXPRESS-G representations of the parametric models.

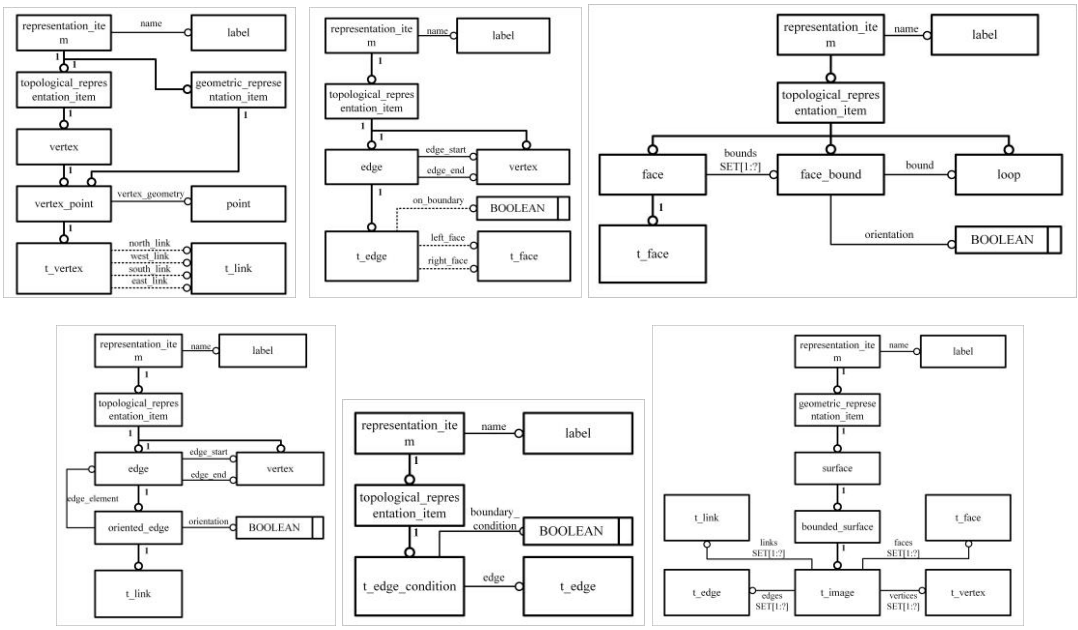

Fig. 2: EXPRESS-G representations of the parametric models: (a) t_vertex, (b) t_edge, (c) t_face, (d) t_link, (e) t_edge_condition, (f) t_image.

- Topological models.

Only two types of entities, *t_node* and *t_connect*, are involved in this group. Another entity *t_node_v4* which inherits the entity *t_node* is introduced for a regular T-spline surface. The entity *t_connect* possesses a set container attribute *nodes* organizing all the involved *t_node* entities. Fig. 3 presents the EXPRESS-G representations of the topological models.

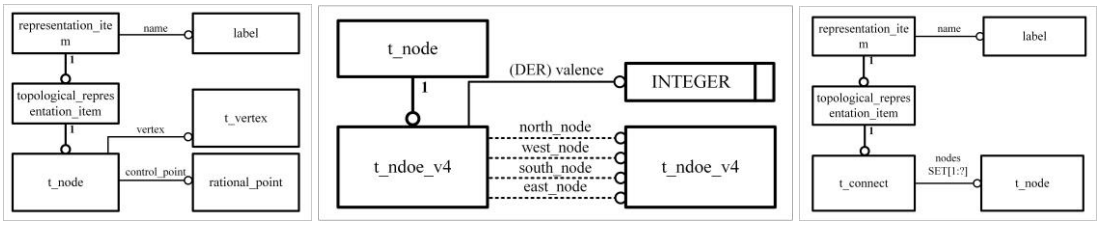

Fig. 3: EXPRESS-G representation of topological domain models: (a) t_node, (b) t_node_v4, (c) t_connect.

- Cartesian models.

This group contains two entities, *rational_point* and *t_pointset*. The entity *rational_point* inherits the *(x, y, z)* coordinate from a *cartesian_point*, and defines a point-based *weight* value for its rational computation. Similarly, the entity *t_pointset* contains all the *rational_point* entities used in a T-spline. Fig. 4 shows the EXPRESS-G representations of the cartesian models.

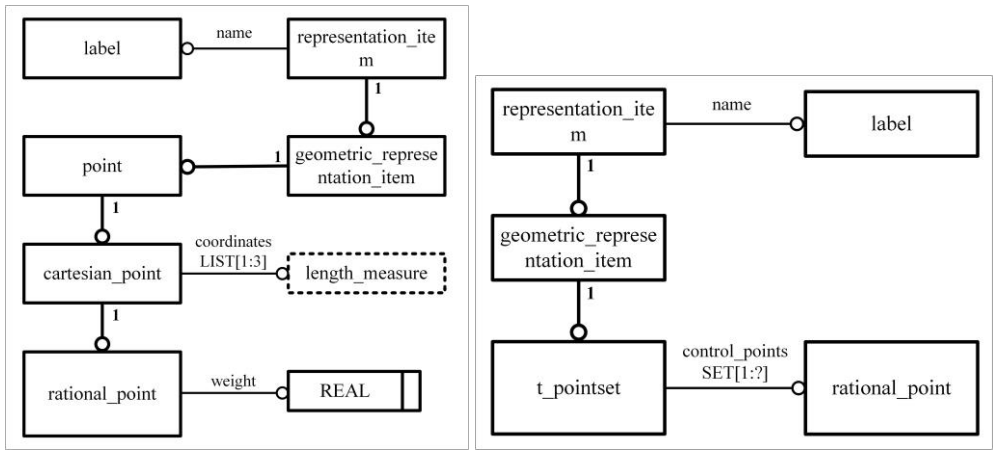

Fig. 4: EXPRESS-G representations of the cartesian models: (a) rational_point, (b) t_pointset.

Prototype system

This paper proposes a prototype system to test the STEP-compliant data exchange of T-spline data models. Three major components have been developed: a TSM-to-STEP converter, a STEP-compliant T-spline parser and a T-spline kernel.

The recent only existing T-spline modeling tool is the T-spline plug-in (developed by the T-splines company) embedded inside the Rhino system. The TSM-to-STEP converter aims to convert a TSM file (generated from Rhino) to a STEP file (P21). It is programmed in the Matlab environment to save massive programming efforts.

In order to read the STEP file into the memory and parse it correctly, a standard procedure called SDAI (Standard Data Access Interface) is implemented to construct the STEP-compliant T-spline parser. All the proposed EXPRESS models were automatically converted into the C++ codes, by which the corresponding STEP reader and writer can be obtained in a relatively short time.

The read and parsed T-spline data models at last has to be processed in a T-spline kernel. This paper develops the T-spline kernel that realizes the proposed data models with substantial algorithms. Fig. 5

shows the STEP-compliant data exchange procedure of T-spline models using our prototype system, and Fig. 6 presents some testing results.

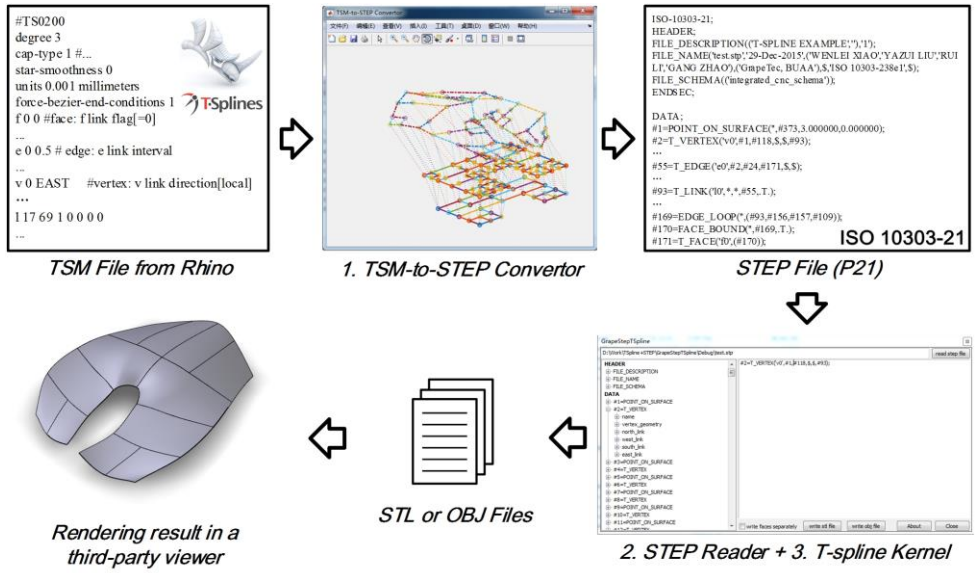

Fig. 5: A prototype system to test the STEP-compliant data exchange of T-spline models.

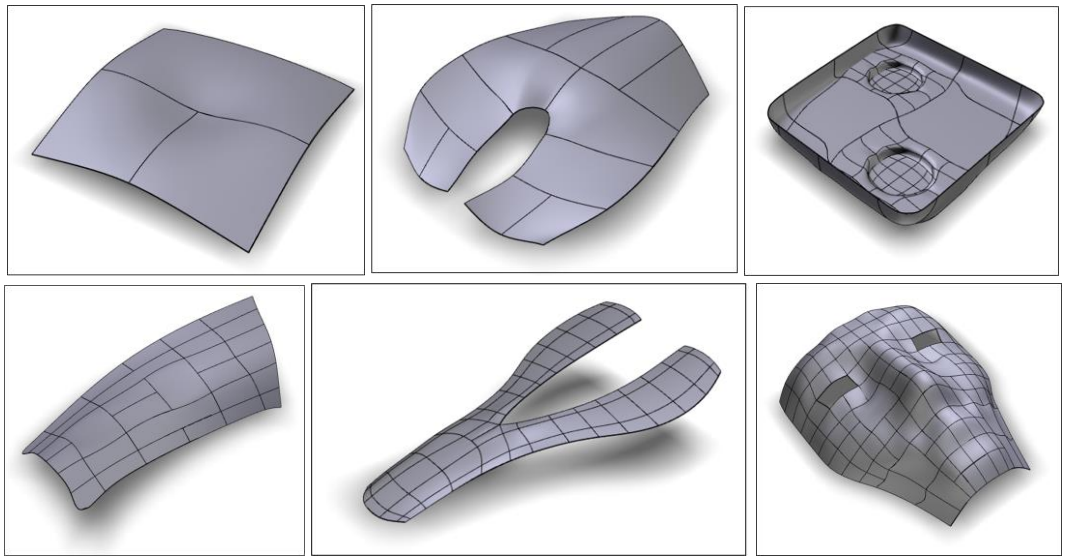

Fig. 6: STEP-compliant data exchange testing results: (a) simple, (b) mouse, (c) gearbox cover, (d) blade surface, (e) bike seat, (f) human face.

Conclusions:

This paper proposes the new T-spline data models with the consideration of data exchange using the STEP format. The T-spline data models have convenience to both human and computer, and is flexible to be converted into STEP definitions. Amounts of EXPRESS models were designed to implement the

proposed T-spline data models, which shows the optimistic prospects in the STEP-compliant T-spline data exchange between different CAx systems. A prototype system consists of a TSM-to-STEP converter, a STEP parser and a T-spline kernel is proposed for the purpose of verification.

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