Architecture for the Control of Machine Tools Adhering to Integrated and Interoperable Digital Manufacturing

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Abstract*–Efforts are being made from different international spheres to enable integrated and interoperable manufacturing that supports the transfer of data between each linked system in the life cycle. Industry 4.0 demands integrated, independent solutions that overcome the interoperability barriers currently present in technology. Work done by the ISO TC 184 (ISO 10303) committee specifies a data structure that supports digital requirements and defines a new information model to support system integration. Furthermore, ISO 23247 defines a framework to support the creation of digital twins applied in manufacturing environments. A digital twin is considered an integrating link in the design, manufacturing, and inspection of a product. This new approach requires solutions in several aspects that allow the complete integration and interoperability of CAx (Computer-aided technologies) systems. This article presents an architecture for machine tool control using an interchange file interpreter from a STEP interchange file (ISO 10303-238:2020) to extract the path information. This technological solution integrates a configurable structure for two different types of parallel robots, remote connection via Ethernet, and flexibility to various parameters. The context of the problem is presented, and the solution is developed to analyze and validate the architecture.

Keywords-- Digital Twins, STEP-NC, Advanced Manufacturing, Industry 4.0.

I. Introduction

The demands made by the digital age, especially in the manufacturing system, lead to the incorporation of mechanical structures within the processes with different configurations that provide dynamic advantages to the process [1]. In this search and selection of increasingly suitable machine tools for specific processes, the possibility of linking parallel robots in manufacturing processes is created due to their characteristics exhibited in operation, such as high speeds in the positioning of the effector, the rigidity exhibited in its actuators, high precision and load capacity in its mobile platform [2], [3], [4], [5]. Studying the dynamic performance of parallel robots, the effects of a variation in its dimensional parameters, seeking integration and interoperability through the implementation of communication protocols, and the development of machine tool language interpreters will allow defining new applications within the advanced manufacturing line [6], [7], [8].

Recently, parallel robotic configurations are increasingly used in additive and subtractive manufacturing processes and pick and place operations [9], [10]. It is also true that the trend in manufacturing seeks to create hybrid systems, increasingly autonomous, where the digital premises properly interposed by industry 4.0 require these systems to communicate integration and interoperability [11] [12]. It is essential to highlight advances in machine tool control languages and to manufacture information exchange files that evolve to an object-oriented perspective and migrate all their previously sequential data structure, such as G-code, for a more robust data structure scalable and hierarchically organized [13]. It was recently included in the ISO 10303-238:2020 standard, additive manufacturing information; this poses new challenges to developing kinematic control of robotics structures applied in advanced manufacturing fields [14] [15] [16]. The development of interpreters for STEP files and the capacity of robotic structures to execute tasks extracted from these neutral interchange files will provide interoperability and integration within advanced manufacturing processes [17] [18] [19].

Also known are some critical limitations of parallel robots in manufacturing processes that must be minimized [20]. The reduced workspace is achieved by the parallel robot comparing its dimensions with other robotic structures; it becomes an optimization problem to determine a correct relationship of parameters that cover a specific workspace [21]. More resources will be required for a larger robot size in its construction, assembly, and operation. Different investigations propose intelligent techniques to obtain the relationship between structural dimensions vs. workspace, with outstanding results to minimize this problem and its effects.

Considering the above considerations, a robotic structure with the possibility of reconfiguring between two different parallel robots, maintaining communication via Ethernet to receive trajectories, and developing a standardized neutral exchange file interpreter seeks to promote the use in specific applications within the advanced manufacturing line. This document presents the relevant aspects in the development of this technological solution [22].

II. Machine controller using STEP-NC data model

When the parallel robot understudy has been designed to perform advanced manufacturing applications within integrated and interoperable digital environments, it is necessary to adopt a data structure that supports current manufacturing requirements [23]. The ISO 10303 standard known as STEP is the result of integrating efforts to represent and support information from the entire life cycle of a product, covering phases of part design, process planning, and manufacturing support [24]. Entities that support additive manufacturing applications were recently incorporated within

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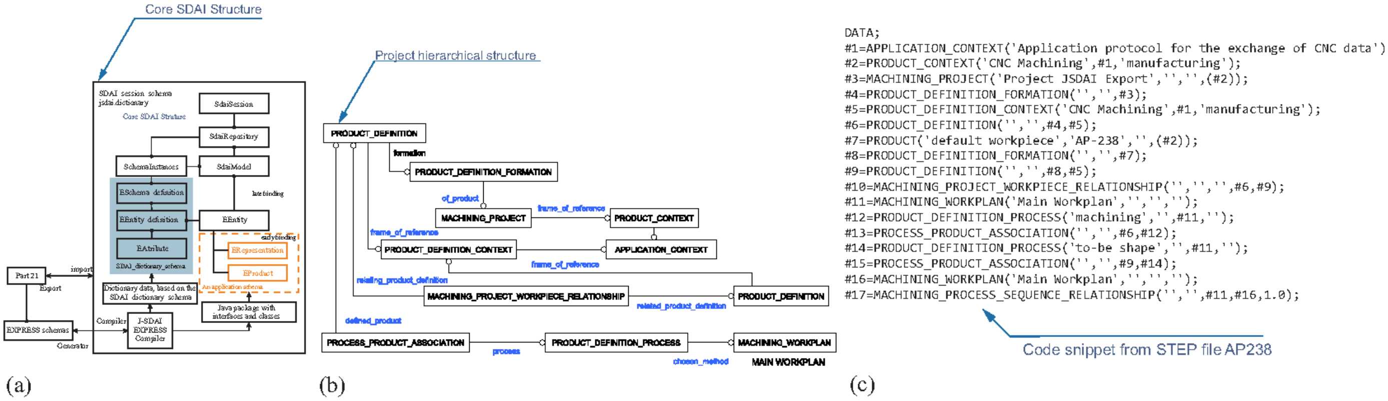

Fig. 1 Interpretation of the STEP standard, (a) JSDAI tool linked to the Java programming environment, (b) UoF Project hierarchy that contains the machining program and information, (c) code snippet from STEP-NC file. Source: Adaptation [25]

the ISO 10303-238 protocol known as STEP-NC. STEP-NC is a technological implementation that replaces the ISO 6983 standard known as G-Code and assumes a relevant role in the advanced manufacturing area. This work incorporates a strategy to obtain the trajectory of the end effector of the parallel robot from a neutral STEP interchange file.

Information decoding begins by analyzing the data structure of a STEP interchange file. According to the standard, a high-level entity called Project structures the entire machining program within the file. Information about the workplan, workpiece, and more relevant data in manufacturing are encoded in this file following the UoF (Unit of Functionality) defined in the standard. Fig. 1 (b) shows a hierarchical diagram corresponding to the UoF Project. In addition to the appropriate computational resources, Java, JSDA, and APIS programming environments run on the Eclipse integrated development environment (IDE). JSDAI is a set of tools and libraries for developing applications based on the ISO 10303 standard and strongly related to the Java programming language. Fig. 1 (a) presents the structure supporting application development as an SDAI ISO 10303-22 implementation (see Fig. 1 (a)). Through EXPRESS schemes, a definition library is created, which are available within the Java environment for application development, enabling read, write and update operations within the information exchange data structure. This information can be read or encoded in neutral files such as p21 of the ISO 10303 standard.

The neutral exchange file is defined in the ISO 10303-21 standard (Part 21: Implementation methods: Clear text encoding of the Exchange structure) known as STEP file or p21. This file contains instances created from EXPRESS schemas with which the information is encoded in two sections: Header and Data section [26]. The information contained in these files is connected through identifiers or tags, and they do not follow a sequential structure allowing the entities to be reused in different application contexts, for example, in design, planning, and manufacturing tasks. Fig. 1 (c) shows an excerpt of code found in a STEP interchange file.

III. Design Parallel Robot Configuration

A. Actuator control system

Both the linear Delta parallel robot configuration and the pyramidal parallel robot configuration have three actuators. Each actuator is made up of a nut spindle mechanism and a Maxon EC- max Brushless motor. The Brushless motor has a stator made up of three-phase windings connected in a star. The supply voltage requires an excitation sequence that depends on the position of the rotor and is carried out through electronic switching with the information supplied by the Hall effect sensors. A model is built that describes the electrical behavior of the motor to implement the control strategies. Table 1 summarizes the parameters of the Brushless EC-Max 22 motor used in constructing the model.

TABLE I
Summary of EC-Max 22 Brushless motor parameters.

Parameters	Symbol	Unit	Quantit y
Resistance	R	Ω	6.930
Inductance	L	mH	0.275
Torque Constant	kM	mNm	13.6
Speed Constant	kN	rpm/V	701
Rotor Inertia	JMotor	gcm^2	2.25
No load current	I_0	mA	103.0
No load speed	n_0	rpm	12100
Inertia	J_{Load}	Kgm^2	0.0013

The resulting equation that represents the behavior of the motor is implemented in a block diagram in Simulink. Fig. **2** shows the block diagram of the motor model.

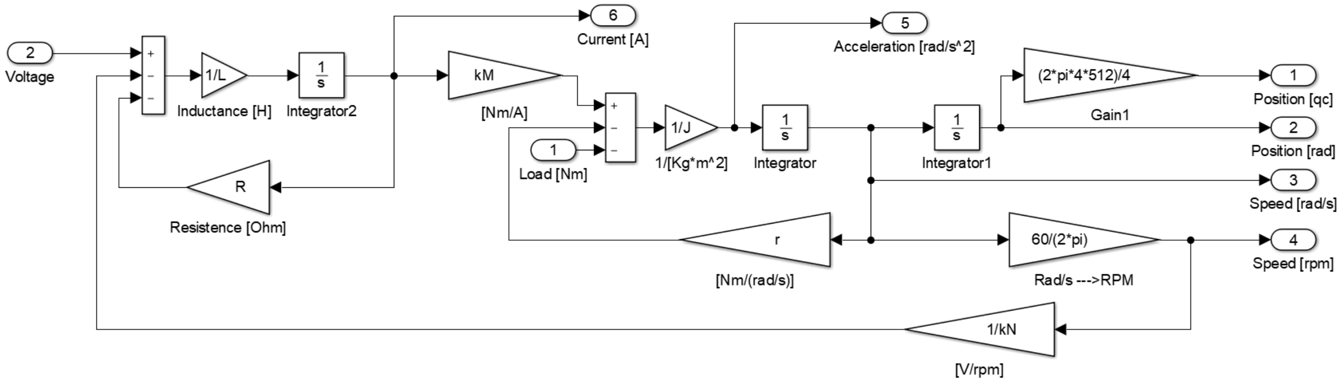

Fig. 2 Representation of the motor electric model.

B. Kinematic study and optimization

Kinematics studies the movement of robots concerning a reference system based on the robot's geometry. Two types of kinematic models are the object of analysis: inverse kinematics model and direct kinematics model. In the inverse kinematic model, the articular coordinates of the actuators are determined to achieve a specific position of the effector. The direct kinematic study determines the mobile platform's position by knowing the actuators' articular coordinates. This document shows the result of the inverse kinematics. For the direct kinematic model, there may sometimes be more than one position for the effector, considering the joint coordinates.

By configuring the structure for the linear delta parallel robot, the inverse kinematic analysis consists in determining the distances traveled by the actuators arranged vertically on the fixed platform for a required position of the end effector, since we know the particular position concerning a reference in the robot of a point to be reached. Fig. **3** (a) shows the geometric model of the parallel delta linear robot, and the fixed coordinate system $O-XY\,Z$ is observed, whose origin is located in the center of the robot's base platform, The Z coordinate is perpendicular to the base, and the X coordinate has direction *OA1*. The moving $P-UV\,W$ coordinate system is located in the center of the effector, where the W coordinate is perpendicular to the moving platform, and the U coordinate has direction *PB1*. In Equation 1, *L1* represents the radius of the robot's base where the actuators are located, *L2* the length of the links that support the mobile platform, and *L3* the radius of the mobile platform that supports the effector. Equation 1 determines the joint position of each linear actuator.

$$d_i = Z + \sqrt{L_2^2 - (X - X_i)^2 - (Y - Y_i)^2} \quad \textit{for i=1,2,3} \quad \textbf{(1)}$$

The geometric model of the pyramidal parallel robot is shown in Fig. **3** (b); it is necessary to specify that, although it uses the same structure, the arrangement of the actuators differs concerning the linear delta robot. The three actuators *A1*, *A2*, and *A3* are anchored in the upper part of the structure, and in the final part, they share the same endpoint, forming an inverted pyramid, hence their name. The mobile platform that contains the robot's end effector is supported through links that are fastened to the actuators arranged in a pyramid. Ball joints are used for these link, actuator, and fixed platform connections, limiting movement due to the opening angle. The action line guides of the three prismatic joints actuated by the actuator are inclined. Fig. **3** (b) shows the vector representation and reference systems of the pyramidal parallel robot. For the analysis, the Cartesian coordinate reference system $O - XYZ$ is located at point O, the base platform's center. The $P-UVW$ coordinate system is located at point P, which is the center of the moving platform. Equation 2 describes the inverse kinematics solution of the pyramidal delta robot. The result indicates that there are two solutions for each actuator, the lower value of the two solutions is the magnitude considered.

$$d_i = (L_i \cdot d_{i0}) \pm \sqrt{(L_i \cdot d_{i0})^2 - L_i^2 - l^2} \quad \textit{for i=1,2,3} \quad \textbf{(2)}$$

C. Determination of the parallel robot workspace

Parallel robots have certain advantages over other configurations such as speed, precision, load capacity, and weight; however, their reduced workspace makes it necessary to implement strategies to balance between reducing robot dimensions and increasing workspace achieved. Finding this solution can be defined as an optimization problem. Through the optimization method, predictable values of parameters that tend to an optimal solution are explored among a possible region of operation. The proposed minimization problem seeks through an objective function that receives the dimensional parameters of each robotic configuration to reduce the total volume of the robot while the robot workspace remains at a fixed value. The resulting volume value with the robot's current parameters is defined as the criterion to be minimized in this

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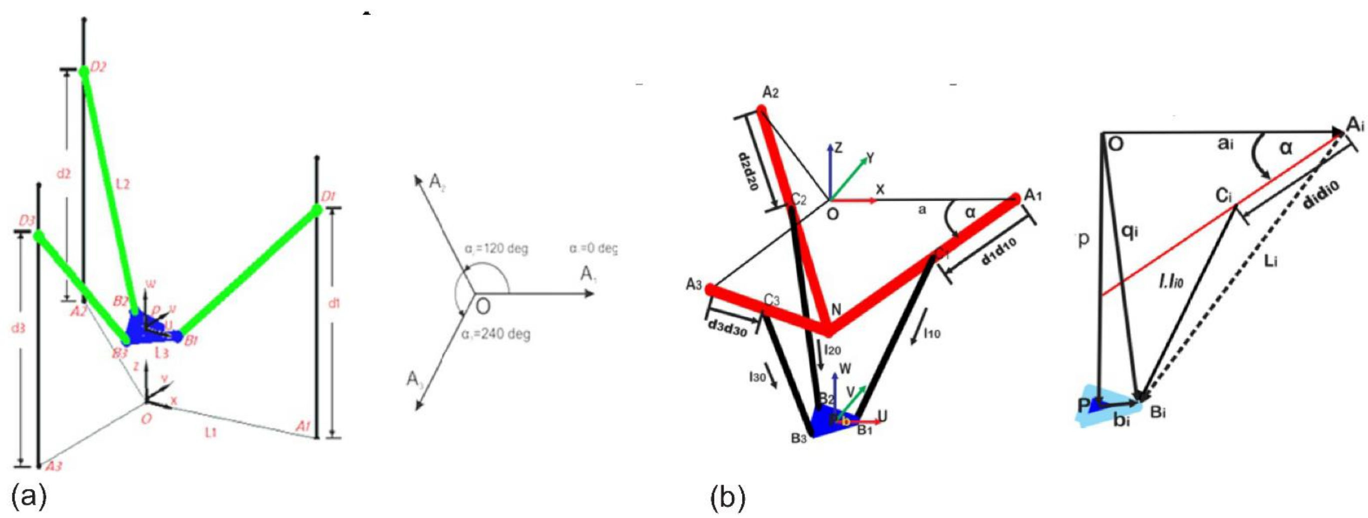


Fig. 3 Geometric model of the configurations allowed on the platform: (a) Linear delta parallel robot geometry, (b) Pyramid Parallel Robot Geometry.

development. These values in each interaction are adjusted within the upper and lower limits given to each variable. Fig. 4 (a) shows the flow diagram that the optimization program follows. Fig. 4 (b) shows the dispersion of the values taken by each dimensional parameter of the robot in search of an optimal solution, the evolution is evident, and the stopping criterion of the algorithm is given because the value of the objective function is stable without changes significant at a minimal value.

To verify the result, a kinematic check is performed with a point cloud covering the workspace. This verification includes the constraints that produce collisions, singularities, and mechanical limitations due to spherical joints.

IV RESULTS

Fig. 5 (a) shows the development of the solution described in this document. A structure that supports two types of different robotic configurations, in turn, the dimensions are variable to analyze the effect that the dimensional parameters of the robot have both on the work area and its functional characteristics. Currently, the technological solution allows testing advances in the interpretation of STEP files to consolidate machine tool interpreters and controllers based on the ISO 10303-238 standard. Fig. 5 (b) shows the circular and linear tray profiles obtained with the linear delta robotic configuration. The parallel delta linear robot and the parallel pyramidal robot allow validating concepts in the area of parallel robotics applied to manufacturing processes in the laboratories of the University of Pamplona, attached to the Mechatronics Engineering program.

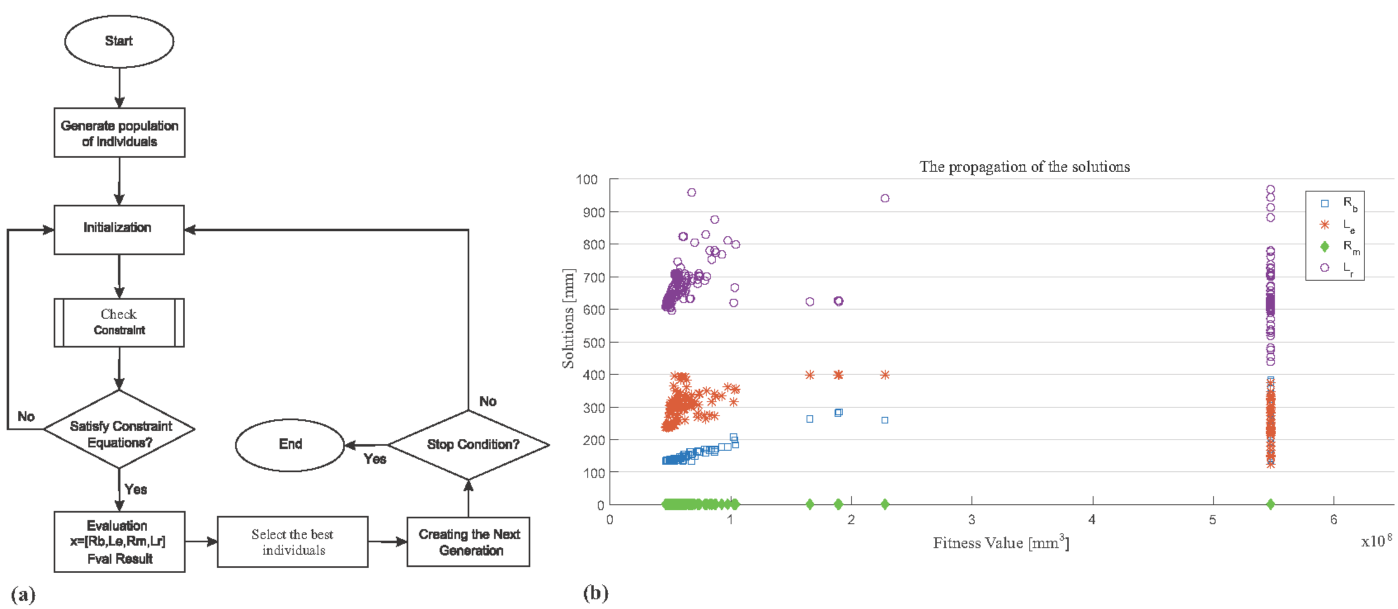
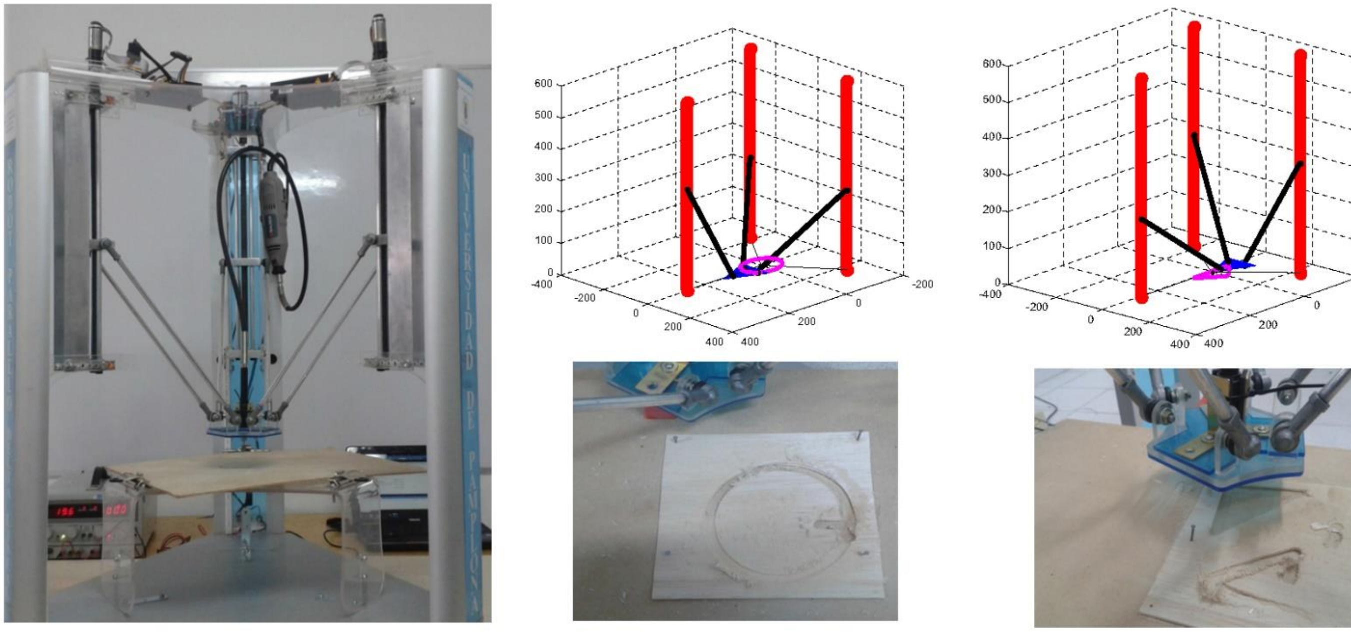


Fig. 4 Optimization of robot dimensions for a predefined workspace:(a) algorithm flow diagram, (b) the propagation of the solutions.



(a) (b) (c)

Fig. 5 Reconfigurable parallel robot to aid in studying robotics concepts

ISO 10303 fully describes the procedure for mapping an application element for which it is necessary to specify a reference path through several interrelated AIM elements. Implementing a digital control architecture requires the creation of an integrated resource interpreter for machine tool control. Each AIM element proposed by ISO 10303 specifies a reference path to its supertype from a built-in resource. The Fig. 6 presents the attributes and relationships between the entities that represent a small part of the data structure involved in the control architecture based on neutral STEP files.

The presented approach for parallel robot control encodes the information needed for path control through a STEP exchange file. The encoded entities define not only the trajectories but also enable writing, managing to provide feedback on the process. The Fig. 6 presents the attributes, entities, and relationships necessary to encode a robotic structure as an assembly of components following the ISO10303 standard. This structure contained within an exchange format allows to break the interoperability barriers and represent any robotic configuration object of control.

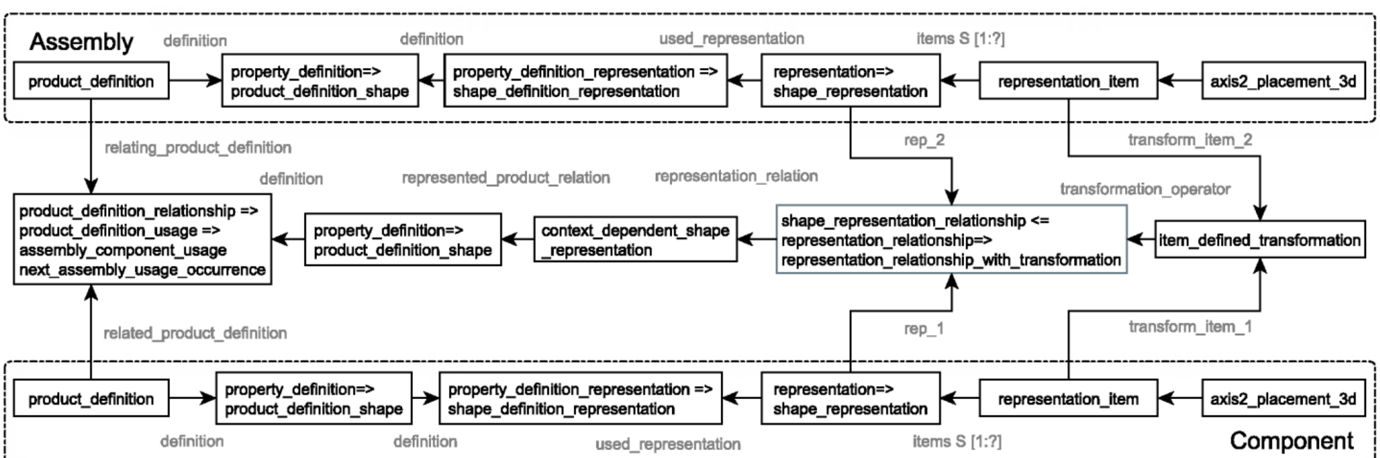


Fig. 6 Attributes, and relationships between the entities representing the assembly data structure contained in STEP files.

III. CONCLUSIONS

The development of the technological solution presented in this document allowed us to identify the main functional characteristics of the linear delta parallel and pyramidal parallel robots. Strategies to maintain balance in the relationship between robot dimensions and workspace will optimize robot dimensions to cover the largest workspace area. The reconfigurable robot fits in a tool to validate concepts associated with parallel robotics and develop interpreters that lead to the control of tooling machines that meet the current integration and interoperability requirements.

The architecture presented is projected on definition-based models, involving neutral exchange files and seeking to meet the information flow requirements in robot control processes. The integration with technologies adhered to the perspective of Industry 4.0, and the concepts of Industry 4.0, promote the integration and interoperability of systems. The presented model integrates the control process with the information demands in the new digital age.

The architecture uses data-neutral structures, eliminating technological dependencies and generating an alternative to overcome the interoperability barriers that make it challenging to link new robotic configurations in manufacturing processes. The presented solution allows sharing of process data, interpretable by different CAx systems. Guaranteeing a standardized exchange, it shares the same syntax and semantics as each manufacturing cycle system.

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