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Abstract

During product development, the verification process should be considered already at the design phase to ensure that the characteristics of the product are measured effectively and reliably. Moreover the verification process may result more effective if the inspector is aware of the specific designer's intents. The development of the new ISO GPS (Geometrical Product Specifications) standards is mainly founded on these considerations. In accordance with the ISO GPS concepts, previous work developed a knowledge based system named Design Guidelines (DGLs). This system provides the designer with the knowledge concerning the manufacturing and verification procedures/tools and better links the manufacturing and verification processes to the designer's activities/needs. Further research then exploited the DGLs to discover the relations among product features determined by a particular manufacturing process.

This work uses again the DGLs to prove that further relations among product features may be also determined by the verification process. This knowledge helps designers understanding the consequences of the modifications applied to the product features required to improve the measurability of the product. Moreover, inspectors can better manage the verification procedure knowing these relations among the product features.

Keywords

Knowledge Based Engineering; Verification Process; Product Features; ISO/TC 213; Geometrical Product Specifications

1 Introduction

Developing new products and optimizing existing ones necessarily implies the careful identification of the characteristics that determine the best compliance with product functionalities and performances (Pahl and Beitz 1995, Otto and Wood 2000, Ulrich and

Eppinger 2000, Ullman 2002). While it is commonplace to think that the manufacturing process characteristics have to be considered when defining product specifications (and as a result great emphasis is placed on bridging the gap between design and manufacturing) (Bralla 1998, Poli 2001, Boothroyd et al. 2002, Andersen 2003, Geng 2004), the same doesn't always happen for the verification process characteristics. Accuracy and precision are also being increasingly emphasized in manufacturing, so that inspection is currently recognized as one of the most important activities during product development (Wasserman 2002). More generally, the conformity of the product to the specifications, and consequently its functions, are guaranteed by the results of the verification process, which should be taken into account starting from the design phase (Srinivasan 2001).

The field generally known as "Design for Verification" has been studied extensively, particularly regarding electronic components and large software systems (Berard et al. 2001, Clarke et al. 2000, Margaria and Melham 2001). This work focuses on the methodologies relating the design phase to the verification process in the mechanical design and engineering field.

The link between the design phase and the verification process is also a goal for the development of new standards: it is one of the fundamental elements of ISO Geometric Product Specification (GPS), on which the Technical Committee ISO/TC 213 has been working since 1995 (ISO/TR 14638 1995). The scope is to develop standards resulting in an integrated system for specification and verification of work piece geometry to unequivocally transmit the designer's intent to verification and the verification needs to the designer in the design phase (ISO/TS 17450 – 1 2000). Figure 1 shows this relation in detail.

FIGURE 1 HERE

Figure 1. Correlation between design and verification as in GPS (ISO/TS 17450 – 1 2000).

The geometrical features defining the components established this link between the specification and the verification step. The geometrical features are thus precisely defined in each world, as well as the relationships between them, by means of terms as nominal feature (design), real feature (physical world), extracted feature (measurement) and associated feature (link between nominal feature and extracted feature) (ISO 14660-1 1999, ISO 14660-2 1999). Thorough the so-called "duality principle", a verification operation corresponds to a specification operation, as in Figure 1, so that the features defined in the specification process are precisely related to those measured (ISO/TS 17450-2 2002, Nielsen 2006).

Regarding measurement equipment, Coordinate Measuring Machines (CMMs) are often specifically considered, being widely recognized as powerful tools for dimensional and geometric tolerance inspection in the manufacturing industry (Bosch 1995). Moreover, the new ISO standards on verification machines are also mainly based on CMMs (ISO 10360-1÷6 2000, ISO/TS 15530-3 2004). The performance of CMMs heavily depends on an efficient inspection plan that ensures reliable results in minimal time (Hwang et al. 2004). Inspection planning is the object of ample research on a wide range of subjects, such as measuring sequences and collision paths (Lin and Chow 2001), setup planning (Ziemian and Medeiros 1998), parts orientation (Kweon and Medeiros 1998), feature based planning and so on (Merat and Radack 1992, Roy et al. 1994, Gu and Chan 1995, Beg and Shunmugam 2002).

This work has been developed within this scenario using a knowledge based approach to evaluate how the modifications applied to a product for compatibility improvement with a particular verification process may affect the characteristics of the product itself. In fact, designers, together with inspectors, should know if and how the modifications applied to a feature to improve its measurability may affect other features not directly related to it. Previous investigations revealed the (often unexpected) relations among product features brought about by exploiting the technological characteristics of the manufacturing process (specifically, the Fused Deposition Modelling process) (Cristofolini et al. 2006). This work completes that research by dealing with the consequences of the modifications determined by the verification process.
The results update and enrich the knowledge content of the tool used here to discover these relations, a knowledge based system for industrial design named Design GuideLines (DGLs) (Filippi et al. 2001, Bandera et al. 2004, Bandera et al. 2005, Filippi and Cristofolini 2007), developed according to the ISO GPS principles. This tool was used effectively to get the result of this research since the DGLs allows for both knowledge formalization and the organization of the relationships among product features..
A short description of the DGLs opens the paper. The procedure for the discovering the relations among product features and for the integration of the results in the DGLs knowledge content is then detailed. A case study to validate the results and verify their quality and applicability closes the paper.

2 The Design GuideLines (DGLs)

2.1 Description

The formal description of the DGLs is the object of other works (Filippi et al. 2001, Bandera et al. 2004, Bandera et al. 2005, Filippi and Cristofolini 2007). To facilitate the comprehension of the present work several fundamental aspects of this system are recalled here.
DGLs is a knowledge based system aimed at effectively helping and leading the activities of designers, manufacturers and inspectors for product design and optimization. The initial consideration is that designers are not necessarily experts in manufacturing and verification processes. Likewise, manufacturers and inspectors are not experts in design. DGLs was thus developed following the GPS concepts and recommendations by designers, manufacturing experts and verification experts, addressing designers, manufacturers and inspectors.
The knowledge structure within the DGLs, called DGLs Building, is quite complex and precise. It is from the result of a thorough investigation in knowledge generation, the cause-effect paradigm, the relationships between the various domains and the different pieces of information involved. The DGLs Building represented as a multi-storey structure has four floors: the Compatibility floor, the Design domain floor, the Manufacturing domain floor and the Verification domain floor (see Figure 2).

FIGURE 2 HERE

Figure 2. The DGLs Building.

Given the complexity of the DGLs adoption, the so-called "DGLs roadmap" was defined. It is composed of three phases: Setup, Configuration and Usage.

In the Setup phase, technological characteristics (for example "Indexed measuring head") and product features (for example "Cavities") are identified and collected in the Compatibility floor. By crossing them, rules are generated to evaluate compatibility among product features and technological characteristics (for example "The cavities must be accessible by the measuring head, considering its inclination"), and actions to obtain compatibility are defined and set in the other three floors (for example, the action "Orient the product to obtain best accessibility to cavities" is put in the Design domain floor). This phase involves designers, manufacturing experts and verification experts.

The Configuration phase implies the quantification of the technological parameters, given specific machines and brands (for example, "βV - Angle of inclination of the head, measured in respect to its vertical position - equal to 105°", considering the CMM equipment DEA Global Image 07-07-07), and is performed by manufacturing and verification experts.

In the Usage phase the compatibility of a specific product (given the parameter values of the product features) is evaluated and the deriving knowledge is activated, in terms of actions leading to the re-design of the product model and the re-configuration of its manufacturing and verification processes. This phase involves, among other actors, designers in their domain. Concerning the possible manufacturing and verification activities, the actors involved are respectively the manufacturer and the inspector, being informed about the specific designer's intents, again according to the GPS principles. Lastly, the DGLs collects the actions of the Design, Manufacturing and Verification domain floors into one or more reconfiguration packages, sort of "to-do lists", with costs associated to them. The users of the DGLs can then select the package best fitting their skills and capabilities.

To emphasize once again the link with the GPS principles, it is worthwhile underlining that all the product features are expressed in terms of sizes, distances and angles, which are geometrical characteristics recognizable in the first column of the ISO GPS Matrix (Figure 3) (ISO/TR 14638 1995).

FIGURE 3 HERE

Figure 3. ISO GPS Matrix (ISO/TR 14638 1995).

2.2 Why DGLs is useful in this work

As indicated before, the aim of this work is to enrich the knowledge content of the DGLs by discovering the relations among product features, given a specific verification process. As established in a previous paper concerning the relations among features determined by several manufacturing characteristics (Cristofolini et al. 2006), the DGLs represents an effective tool to achieve this result since:

- It allows a formal description of the product features and technological characteristics (with the related process parameters);
- It clearly identifies the role of the different actors (designers, manufacturing experts, verification experts) who contribute to knowledge generation;
- The procedure to define the rules and to derive the actions is rigorously represented. This is particularly interesting given that actions are one of the key-points of this research;

- In the DGLs, knowledge management allows to recognize and use the different kinds of information as easily and effectively as possible, so that the inference process finds optimal conditions to obtain the best results.

3 Discovering the relations among product features

Now that the DGLs has been described, it is possible to go on to describe the application of the procedure on a case study to discover the relations among product features uncovered by means of the verification process.

Firstly, the Setup phase of the DGLs is executed in order to generate the knowledge needed for the next steps of the procedure. This phase is made up of three steps: (1) Identification of verification characteristics and product features; (2) Generation of rules and compatibility evaluation and (3) Generation of actions. The fourth step, Determination of the relations among product features, is the core of the procedure and consists in performing the activities for the analysis of the content of the knowledge base and discovering the relations.

These steps will be described in detail further below. The description is integrated with some tables containing sample data to increase the argument readability and comprehension.

3.1 Identification of verification characteristics and product features

In this step, the technology of the CMMs and the class of the products that it measures are formalized in terms of characteristics and features, respectively. Each of them has its own parameters. Table 1 (left side) shows several verification characteristics with related parameters and Table 2 (left side) shows the geometrical features used to describe the selected class of products. The product features may be referred to those used in the previous work where the relations among features determined by manufacturing characteristics were found (Cristofolini et al. 2006). Obviously, these features are also meaningful when related to the verification process as the aim of future work will be to achieve comparison and merging between the relations found considering both the manufacturing and the verification processes.

3.2 Generation of rules

Product features may be related to the technological characteristics and the expert of the CMMs expresses this in the form of rules established for each characteristic/feature pair. For each rule there is an expression used to evaluate quantitatively the compatibility of the product with the verification technology. The list of rules is shown in Table 3 (left side).

3.3 Generation of actions

In this step, the technology experts define the actions determined by each rule and formulate them in a "verb-accusative-goal" format. Simultaneously, the domain where actions and their costs apply (here reported in the [1..10] range) are set. It is worthwhile remembering that the aim of the actions is to achieve compatibility with the verification technology when the DGLs shows that the product is not measurable using the verification technology chosen. Clearly, if the actions have to be applied in the Design domain, their application must be evaluated with respect to the product's functional requirements. The list of actions is shown in Table 4. In this Table, the rule R1 doesn't determine any action because no actions are possible if the bounding box of the product exceeds the measuring workspace: in that case, different measuring equipments must be chosen and the DGLs will be applied again to the new scenario.

3.4 Determination of the relations among product features

The information collected before is used here to highlight discover the possible relations among product features. The inference procedure runs as follows. Actions with the same verb-accusative pattern are grouped together (see Table 5 left side), even if their goals are different (given that they derive from different rules). In fact, they require the same activities to be performed (for example, the modification of the same process parameters) since they have the same pattern. These same activities could influence all the features where the grouped actions come from. This is why these features may be considered related each other. In order to discover the relations among product features, the representation of the results classifies the groups of actions in the two domains (design and verification) separately, making it simple to recognize the domain where the various actions take place [or took place?]. Table 5 (right side) shows the relations found in the case in point, expressed in terms of product features and related to the Design domain and to the Verification domain respectively. The result is represented both in a qualitative and in a quantitative way, also showing the parameters of the related features. This representation seems to be the most usable one because it shows directly which parameter could be affected by each modification applied.

The classification of the results by domain coherently achieves the aim of this study, [and has to be read as follows].

For what concerns the Design domain, the results of the procedure state that the feature Overhangs/Sloped surfaces (F3) is related with the feature Bounding box (F1). This means that a modification of the parameters characterizing the Overhangs may imply the modification of those of the Bounding box. For example, if the designer modifies some protruding overhangs by adding slides or flatting surfaces to make clamping easier, this action may imply some modifications of the features defining the bounding box too. Knowing this relation may lead to search for the optimal solutions the first time, avoiding further re-design phases.

In the Verification domain, the results state that the feature Overhangs/Sloped surfaces (F3) is related to the feature Cavities (F4). This means that the presence of overhangs/sloped surfaces has to be considered together with the presence of cavities (and vice-versa), when defining a measurement procedure that aims at improving the measurability of these features. Knowing this relation may help in defining more effective and reliable measurement procedures, thus minimizing re-positioning of the product and measuring head.

All these results also show to be coherently organized with ISO GPS concepts, both in the features definitions and in the search for establishing links between the specification and the verification phases.

To be thorough, it must be pointed out that the inference procedure described and used here is based on actions coming from rules derived by verification characteristics and the relations are found only if the considered action involves, each time, the same activities for other features. In other words, it is necessary to underline that this procedure only uncovers the relations among features determined by the verification characteristics. .

4 Using the discovered relations with the DGLs

Once the relations among product feature have been discovered, they are used to update the knowledge content of the DGLs and they constitute a great added value for the DGLs effectiveness. In fact, for example, the reconfiguration packages are enriched with all this information to help the user in performing the required actions safely.

To validate the results of this research and to clarify their role in the re-configuration process, what follows is the description of the DGLs adoption (Configuration and Usage phases) in a real situation.

Table 1 (right side) shows the value of the verification characteristic parameters for the CMM used here, a DEA Global Image 07-07-07.

Table 2 (right side) shows the parameters of the features describing the mechanical part used in this case study and drafted in Figure 4.

FIGURE 4 HERE

Figure 4. Draft of the mechanical part used for the case study.

Table 3 (right side) reports the compatibility values evaluated by using the expressions for each rule of the table.

Table 4 (right side) marks as "activated" only the meaningful actions (the ones coming from compatibility values equal to zero) for the next steps of the procedure.

Table 6 reports the two reconfiguration packages resulting from the DGLs adoption. They have been generated collecting and combining the activated actions and their goals. The cost of the two reconfiguration packages is the same, but package 1 contains warnings for both the actions, that means that both actions are likely risky because they may influence more features. It is thus preferable to choose package 2, where only one action is likely risky, while the other is safe. This way, further knowledge is given to the DGLs users, which can choose the most convenient package not only on the basis of the cost.

5 Conclusions

The purpose of this work was to discover the relations among product features, given a specific verification process. This to help designers and inspectors during the re-design and verification activities aimed at making the product as compatible as possible with the verification process, according to ISO GPS principles. The Design GuideLines (DGLs), a knowledge based system developed in previous research was used to find these relations, which sometimes appear quite unpredictable. The inference procedure is not straightforward; the DGLs knowledge structure and a clear roadmap for their application made this research practicable and effective. The results are represented in tables, informing the users that the modification of some product features may affect others unexpectedly. This information is given both in a qualitative way (product features) and in a quantitative one, thus recalling the values of the product parameters involved. The quality of the results is under evaluation in many of its aspects and future papers will report the results of these evaluation activities. Subjects of further study also include the comparison and merging of these results with the ones obtained by considering the manufacturing process and the exploitation of the product feature relations in optimizing the algorithm for the generation of the reconfiguration packages.

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Table 1. Verification characteristics of the CMMs with related parameters (left) and parameter values for a specific technology (right).

Characteristic				DEA Global Image 07-07-07 parameter values
Label	*Name*	*Description*	*Parameters*	
V1	Verification workspace	Volume of the verification workspace	xVmax, yVmax,zVmax: dimensions of the verification workspace	xVmax=700 mm yVmax=700 mm zVmax=660 mm
V2	Indexed measuring head	Possible inclination of the measuring head	βV: Angle of inclination of the head, measured in respect to its vertical position	βV = 105°
V3	Probe	Kind of probe used for verification	ϕP_min: diameter of the probe	ϕP_min=1 mm
			lP_max: length of the probe	lP_max=200 mm
V4	Clamping tools	Limitations due to the clamping tools	xC_min, yC_min, zC_min: Dimensions defining the contacting area with the clamping tools	xC_min=5 mm yC_min=5 mm zC_min=5 mm

Table 2. Product features of a particular class of products with related parameters (left) and parameter values describing a specific product (right).

Feature				Specific product parameter values
Label	*Name*	*Description*	*Parameters*	
F1	Bounding box	Overall dimensions of the product	X, Y, Z: maximum dimensions	X=304 mm Y=159 mm Z=106 mm
F2	Minimum dimensions	Minimum dimensions in the product	x, y: minimum dimensions in horizontal plane	x=16 mm y=3 mm
			z: minimum thickness	z=3 mm
F3	Overhangs/ Sloped surfaces	Overhangs and protrusions	α: overhangs angle (angle between the vertical wall and the overhang)	α=90°
F4	Cavities	Thorough and blind holes, undercuts and other cavities	xCav, yCav: minimum dimensions determining a cavity	xCav=24 mm yCav=20 mm
			dCav: maximum depth of a cavity	dCav=16 mm
			β: angle between the vertical wall and the axis of the cavity	β=90°
			dx, dy, dz: minimum distances between cavities surfaces and walls	dx=18 mm dy=3 mm dz=3 mm

Table 3. Rules generated by crossing product features and technological characteristics (left); compatibility values (right).

Rule				Compatibility values
Origin	*Label*	*Name*	*Compatibility expression*	
F1 vs. V1	R1	Dimensions defining the bounding box of the product must be smaller than maximum dimensions of the verification workspace	E1=1 IF Z<zVmax AND X<xVmax AND Y<yVmax ELSE E1=0	1
F1 vs. V4	R2	Dimensions defining the bounding box of the product must be compatible with the need for clamping tools	E2=1 IF X>xC_min OR Y>yC_min OR Z>zC_min ELSE E2=0	1
F3 vs. V2	R3	The overhangs must be accessible by the measuring head, considering its inclination	E3=1 IF $\alpha > (\beta V - 30°)$ ELSE E3=0	0
F3 vs. V4	R4	The presence of overhangs must be compatible with the need for clamping tools	E4=1 IF $\alpha \geq 90°$ ELSE E4=0	1
F4 vs. V2	R5	The cavities must be accessible by the measuring head, considering its inclination	E5=1 IF $\beta > (\beta V - 30°)$ ELSE E5=0	0
F4 vs. V3	R6	The dimensions of cavities must be compatible with the diameter and the length of the probe	E6=1 IF MIN(xCav, yCav)$\geq$3*ϕPmin AND dCav<lPmax ELSE E6=0	1

Table 4. The actions generated by the expert of the CMMs (left) and the activations (right) as coming from the compatibility evaluation.

Domain	Action						Activated Actions
	Origin	*Label*	*Verb*	*Accusative*	*Goal*	Cost	
Design	R2	A1	Add	slides or flat surfaces	to make the product compatible with the clamping tools	8	
	R4	A2	Add	slides or flat surfaces	to make the overhangs compatible with the clamping tools	8	
	R6	A3	Over-dimension	the cavities	to obtain compatibility between the dimensions of cavities and probes	5	
Verification	R3	A4	Orient	the product	to obtain best accessibility to the overhangs	4	√
		A5	Rotate and incline	the measuring head	to obtain best accessibility to the overhangs and the minimum re-positioning	2	√
	R4	A6	Orient	the product	to get compatibility with the clamping tools	4	
		A7	Rotate and incline	the measuring head	to avoid contact between the probe and the clamping tools	2	
	R5	A8	Orient	the product	to obtain best accessibility to cavities	4	√
		A9	Rotate and incline	the measuring head	to obtain best accessibility to cavities and the minimum re-positioning	2	√
		A10	Change	the probe	to obtain minimum re-positioning (using a star-probe)	2	√

Table 5. The groups of actions sharing the same pattern verb-accusative (left) and the related features (right).

Domain	Actions		Group
	Labels	*Verb-Accusative*	
Design	A1 A2	Add slides or flat surfaces	G1
	A3	Over-dimension the cavities	G2
Verification	A4 A6 A8	Orient the product	G3
	A5 A7 A9	Rotate and incline the measuring head	G4
	A10	Change the probe	G5

Related features	Related feature parameters
Bounding box Overhangs/Sloped surfaces	X, Y, Z α
Overhangs/Sloped surfaces Cavities	α xCav, yCav, dCav, β, dx, dy, dz
Overhangs/Sloped surfaces Cavities	α xCav, yCav, dCav, β, dx, dy, dz

Table 6. Reconfiguration packages.

	Domain	Actions			
		Name	*Goals*	*Warnings (related features)*	*Cost*
Reconfiguration Package 1	Verification	Orient the product	to obtain best accessibility to the overhangs AND to obtain best accessibility to the cavities	Overhangs/Sloped surfaces Cavities	4
		Rotate and incline the measuring head	to obtain best accessibility to the overhangs and the minimum re-positioning AND to obtain best accessibility to cavities and the minimum re-positioning	Overhangs/Sloped surfaces Cavities	2
				Total number: 4	Total: 6

	Domain	Actions			
		Name	*Goals*	*Warnings (related features)*	*Cost*
Reconfiguration Package 2	Verification	Orient the product	to obtain best accessibility to the overhangs AND to obtain best accessibility to the cavities	Overhangs/Sloped surfaces Cavities	4
		Change the probe	to obtain minimum re-positioning (using a star-probe)	-	2
				Total number: 2	Total: 6

LIST OF FIGURE CAPTIONS

Figure 1. Correlation between design and verification as in GPS (ISO/TS 17450 – 1 2000).

Figure 2. The DGLs Building.

Figure 3. ISO GPS Matrix (ISO/TR 14638 1995).

Figure 4. Draft of the mechanical part used for the case study.

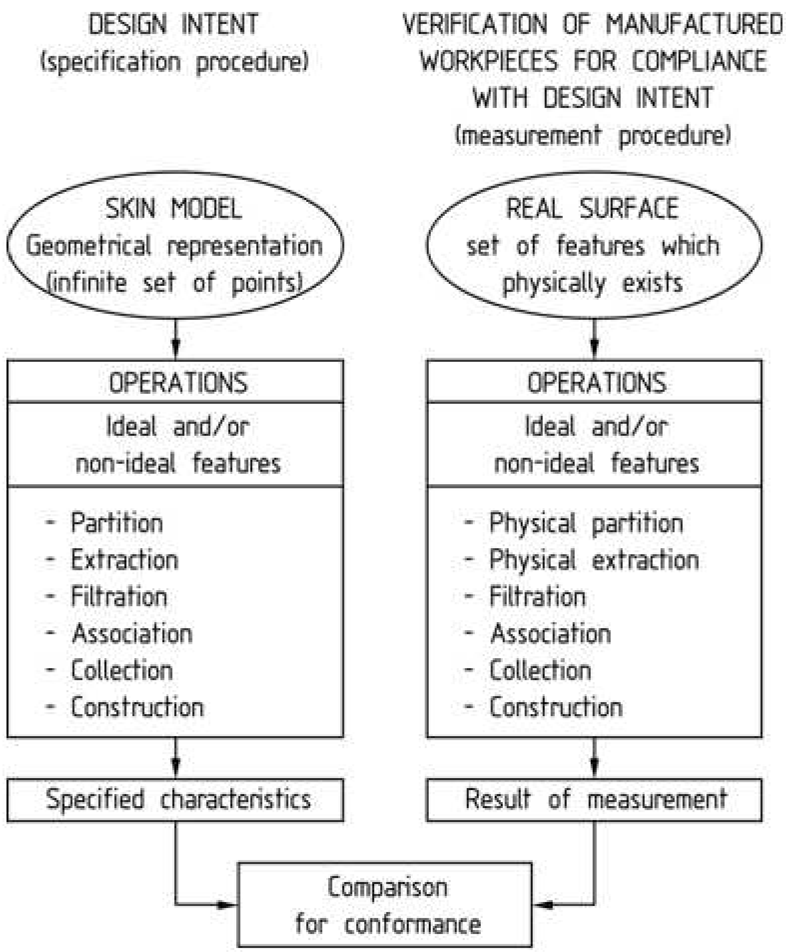

Figure 1. Correlation between design and verification as in GPS (ISO/TS 17450 – 1 2000).
104x128mm (96 x 96 DPI)

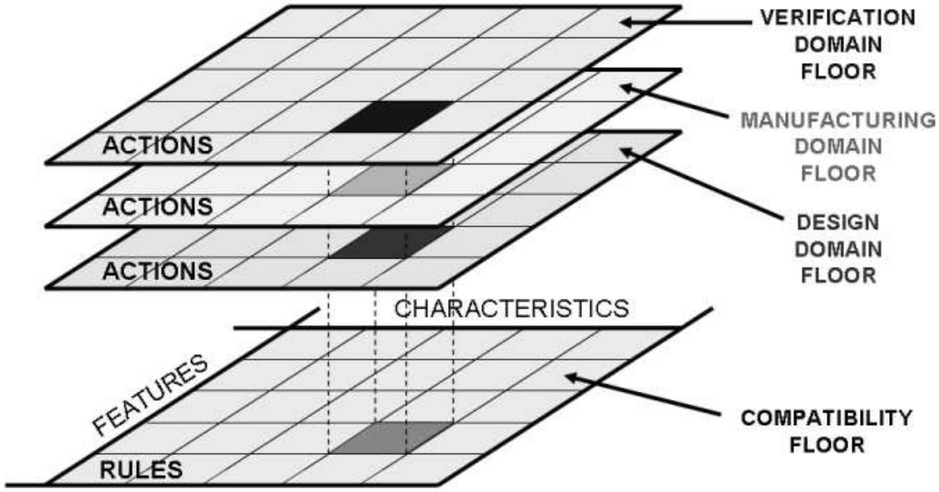

Figure 2. The DGLs Building.
190x105mm (96 x 96 DPI)

ISO/TR 14638:1995(E) © ISO

GLOBAL GPS STANDARDS			
1, 370, 10209-3, 10579, VIM, GUM			

GENERAL GPS STANDARDS			
Chain link number		1	2
Geometrical characteristic of feature	Geometric sub-characteristic of feature or parameters	Product documentation indication - Codification	Definition of tolerances - Theoretical definition and values
Size		129 (R), 286-1, 406-1	286-1, 286-2, 1829
Distance	"Step" distance (height)	129 (R), 406	
	Distance between real or derived feature and derived feature	129 (R), 406	
Radius		129 (R)	
Angle (tolerance in degrees)	Angle between real features	129 (R), 1119 (R)	
	Angle between real or derived and derived feature	129 (R)	

Figure 3. ISO GPS Matrix (ISO/TR 14638 1995).
261x205mm (96 x 96 DPI)

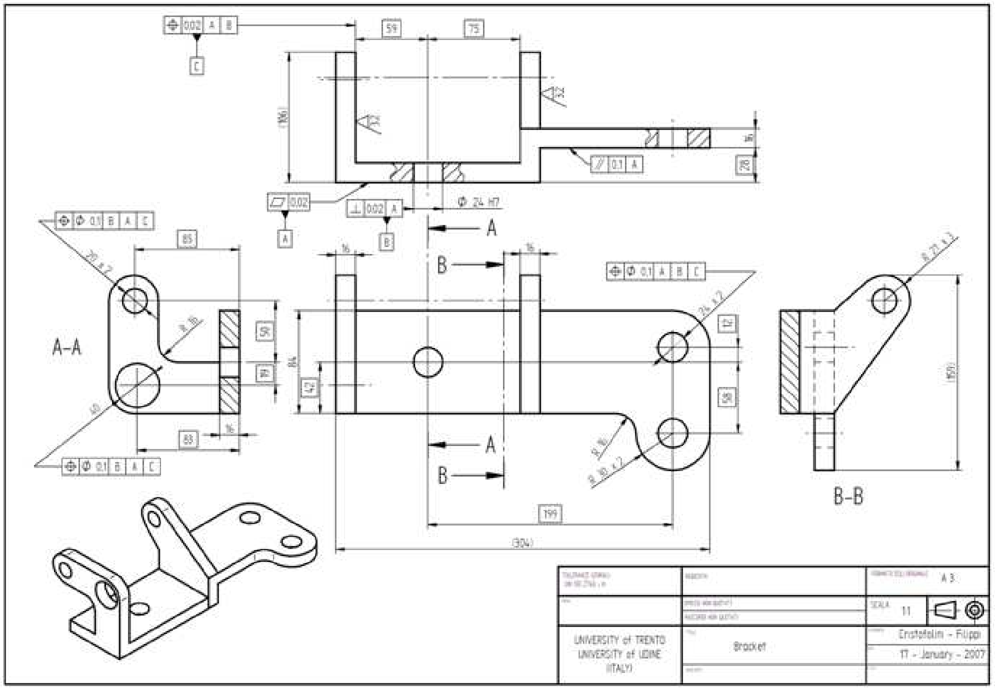

Figure 4. Draft of the mechanical part used for the case study.
182x129mm (96 x 96 DPI)