Chapter 2

Methods and Solutions for Micro-Product Design

A CLASSIFICATION AND CODING SYSTEM FOR MICRO-ASSEMBLY

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Abstract This paper presents the development of a standard classification and coding system for micro-scale assembled devices that can link micro-assembly concepts and technologies to the attributes of the assembly components and their interrelationships that define the assembled device/product. The proposed system is based on an n-digit coding of both individual parts as well as the assembly. The coding scheme identifies a form code, a material code and a process code for both parts and the assembly and then partitions each into the relevant attributes. A specific example of coding of the parts of a miniature spin bearing has been considered to illustrate the applicability of the coding system.

Keywords coding, classification, micro-parts, micro-assembly, spin bearing

1 Introduction

Assembly has taken on considerable importance in the field of micro-systems manufacturing with a drive towards increasing miniaturization and function integration. IC fabrication and packaging and MEMS precipitated the need for assembly of very small parts and this movement rapidly spread into various other applications such as microfluidic systems, optical MEMS, and many others. As researchers strive to transform nanoscience and technology into useful engineering systems through integration that requires the bridging scaling laws across the nano-micro-meso domains, new design tools must be forthcoming to carry out micro-assembly of critical components in a wide range of telecommunication, medical, defense, etc., applications.

Developing a systematic architecture for assembly has been a driving force of research efforts as seen in the work of Hollis et al. leading to development of tabletop precision assembly systems [1]. Likewise, Kuo et al. [2] have carried out assembly of a

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150 μm diameter pin with a 200 μm thickness plate under the guidance of three laser fibers creating a Molten Separation Joint (MSJ). Another interesting example of micro-assembly is a commercial unit by Klocke Nanotechnik with four nanorobotics axes (X, Y, Z-stages plus microgripper) and a joystick, which is capable of carrying out assembly of glass fibers, laser diodes, RF-mixer, micro systems or the handling of thin wires, gears, SMD-chips and micro sensors [3]. Furthermore, considerable research has been done on the development of specific micro-assembly tools and methods including work on visual servoing, sensor-based assembly and a vacuum handling tool [4-13]. At the micro-assembly systems design and planning level, Kurniawan et al. have reported an attempt at developing a morphological classification of hybrid microsystems assembly [4] and several research works dealing with the planning for assembly have also been reported [5-6].

Although there has clearly been considerable work on micro-assembly in the last several years, much of the work in this field is still ad-hoc with solutions presented to very specific problems. Furthermore, the proliferation of microsystems technologies suggests that it will become increasingly important to approach the problem of micro-assembly more systematically to insure that all the relevant available technologies can be brought to bear on a given problem. To this end, this research deals with developing a comprehensive design tool for micro-assembly. This tool will be comprised of three essential elements: a) a hierarchical classification and coding system for a micro-assembly and its parts that captures their basic attributes; b) a database of technologies based on the current state-of-the-science that can be used to address micro-assembly requirements; and, c) a set of design rules and algorithms that link assembly and part attributes to the database for the selection of appropriate technologies. Figure 1 illustrates this concept in detail. This paper addresses the first of these essential elements: an assembly/part classification and coding system.

In this paper, we consider a multi-tiered framework involving coding of assembly and coding of parts. Individual parts of the code deal with form, material and process parameters. The digits in the coding scheme are justified with mathematical and/or logical analysis as required, such as analysis of forces, geometry, current and past experimental results in micro-assembly, etc. A case study on assembly of a miniature spin bearing is used to demonstrate the applicability of the coding scheme.

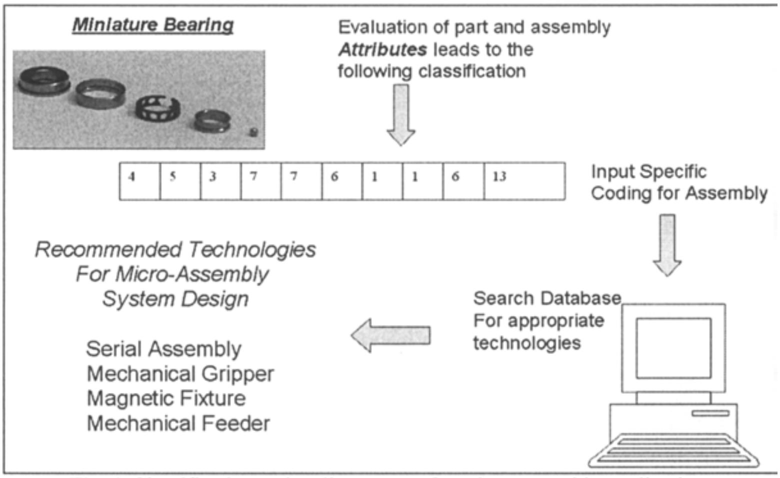


Fig. 1. Classification and coding system for micro-assembly applications

2 Overview of Coding of Assembly and Parts

In developing the coding system, it was helpful to identify several micro-scale system/device families of parts that required assembly. These "case studies" were useful in creating meaningful attributes that define the system. A study of each part family led to the development of a set of parameters that uniquely define the part characteristics/requirements and are relevant to the micro-assembly process. Both parts and the assembly were found to have separate unique characteristics. These characteristics are geometric, materials, and process-based. Therefore, the coding for both parts and assembly was classified as having a form code, a material code and a process code, each with the generic structure **1234 56789 AB...**, which uses up to nine digits and some number of letters. Each digit represents a part or assembly attribute and each attribute may ultimately be defined by a range of numbers, e.g., 0-9, 0-99 etc. The form code is used for storing geometry-related information, the material code is used for storing information related to material properties of critical parts of the assembly and the process code is used for storing information related to assembly environment and surface properties of the individual components. Table 1 outlines the scheme for coding of assembly, while Table 2 outlines the scheme for coding of parts.

Table 1. Coding of Assembly

Assembly Form (Code digit)	Assembly Material (Code digit)	Assembly Process (Code letter)
Distinctly different parts (1)	Material of most critical part (3)	Assembly environment (A)
Type of assembly (2)	Number of dissimilar materials (4)	Surface properties of assembly exterior (B)
	Tolerance of most critical part (5)	
	Tolerance of most critical joint/interface (6)	
	Weight of assembly (7)	

Table 2. Coding of Parts

Part Form (Code digit)	Part Material (Code digit)	Part Process (Code digit)
Part Symmetry (1)	Material (4)	Positioning and Alignment (7)
Geometrical Shape (2)	Mass (5)	Surface Roughness (8)
Characteristic Dimension (3)	Specific Stiffness (6)	

3 Identification of Attributes for Coding

An extensive study of part/assembly attributes for micro-assembly yields insights into the parameters that are needed to serve as a basis for identification of the key technologies necessary for assembly as shown in Fig. 2. These parameters can be used as the basis for development of the classification and a coding system. Specifically, different sub-assembly operations for parts of different dimension ranges were related to the gripping, positioning, sensing and forces during assembly. The table is drawn up based on several micro-assembly experiments that have been performed and understood over the years [2-9]. The first column shows sub-assembly operations that are related to the geometry and symmetry of the parts. The second column deals with part size. The remaining columns outline the technologies needed to carry out the assembly for the given parts.

Consider the manipulation of rectangular blocks as shown in the third example. For the given dimension ranges, it is seen that ortho tweezers on a 3-DOF stage are helpful in manipulating the parts for assembly. It is further seen that orthogonal tweezers work well on only polygonal objects such as rectangular blocks and not for spherical parts. This helps us establish geometry as an important part attribute for coding. Now, considering the fourth example, which is a pin-plate assembly, we see that a molten separation joint using µ-EDM and Nd-YAG laser is needed for assembly with CCTV being used for seeing the parts [2]. The dimensions of the parts are of the order of a few hundred microns and, hence, we do need a specialized vision system but it need not be of a very high resolution such as SEM or TEM. Further, the need for a joining process arises due to the specific geometries which are a cylinder and a plate with contrasting symmetries, viz., rotational and reflective, respectively.

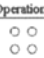
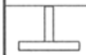
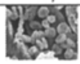
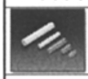
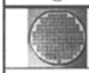
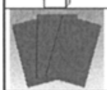
Subassembly Operations	Part Size	Gripping	Positioning	Sensing	Procedure/Forces
	10-100 μm	Needle shaped handling tool	3-DOF stage (to bring the balls in the focus of the microscope)	SEM, Optical	Mechanical – Pick –and-place
	~ 100-1000 μm x 100-1000 μm	Optically transparent electrostatic	4-DOF stage (to align wafers and bring them in focus)	CCD	Electrostatic
	~100-1000 μm x 100-1000 μm x 100-1000 μm	Ortho tweezer	3-DOF stage	--	Mechanical
	~50-500 μm dia, 50-500 μm thick	Clamping	μEDM+Nd.-YAG Laser	CCTV	Joining – Molten Separation Joint
	100 – 500 μm	Vacuum gripper	3-DOF	CCD	Mechanical
	1-2 mm x 1-2 mm	Vacuum gripper	--	--	Non contact handling
	10 nm – 100 μm	Vacuum gripper, Optical gripper	--	SEM, TEM, Optical microscope (plant cells)	Non contact handling
	100 μm - 500 μm	Capillary gripper, Two fingered microgripper with thermal glue	--	--	Pneumatic forces
	few mm – 1 cm	Friction gripper	--	--	Mechanical
	1 – 5 mm	Pneumatic gripper	--	--	Mechanical
	10 μm – few mm	Electrostatic gripper	--	--	Electrostatic
		Magnetic gripper	--	--	Magnetic
	--	Bernoulli gripper	--	--	Hydraulic
	--	Air cushion gripper	--	--	Non contact handling
	100 μm – few mm	Ultrasonic gripper	--	--	Non contact handling

Fig. 2. Micro-Assembly Technologies Organized by Part/Assembly Attributes

Likewise, for the twelfth example concerning assembly of semi-conductor wafers, the use of a magnetic gripper is facilitated by the part being made of magnetic material. This helps us establish part material as an important attribute for coding. This analysis thus leads to the identification of the parameters that are important as both part and assembly characteristics such as symmetry, shape, dimensions, material, alignment and assembly environment, which then leads to broader generalization as form, material, and process codes for both parts and assembly.

4 Coding of Parts

4.1 Part Form Code

The part form code is required to provide key geometry-related information about the part including part symmetry, part shape and part size.

1st digit – Part Symmetry

A part is said to have "exact rotational symmetry" if it can be defined by an envelope that is a solid of revolution or it has n-fold rotational symmetry, "exact reflective symmetry" if it is a prismatic solid or thin-wall part with symmetry about a plane through the center of gravity of the part, and "partial symmetry" if it has portions of the boundary that can be identified as symmetric. It is seen that cylinders, spheres, cones, wafers, rings, gears, etc., can be classified as having rotational symmetry, while rectangular boxes and prisms can be classified to have reflective symmetry. Irregular objects have rotational, reflective and partial symmetry or no symmetry at all. Symmetry can be exploited for gripping, part insertion, fastening, orienting and feeding.

2nd digit – Geometrical shape

The geometrical shape determines the surface(s) for pick-and-place operations, visibility of the part under a microscope and the gripping system. For instance, orthogonal tweezers can easily pick up rectangular parts but not spherical. Moreover, part shape also determines mating surfaces for assembly. Various common geometrical primitives have been identified and linked to their respective symmetries as shown in Fig.3.

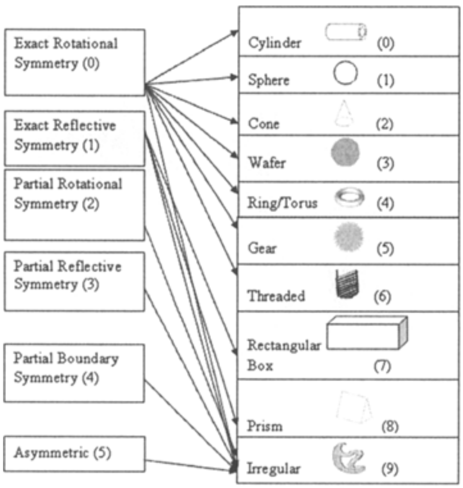


Fig. 3. Part Symmetry and Geometry

3nd digit – Characteristic Dimension

The size of a micro-part determines the magnitude of different forces in play during assembly, visibility, ease of handling and manipulation, particularly part gripping and release, and often, the overall sequence of assembly as well. However, it is useful to find a single measure for the dimension of a part, which may often have different dimensions in different planes. This would not only give an idea of the overall size of a part, but also make the part code more compact. Figure 4 shows an illustration of projected dimensions for a rectangular box. Several possible measures for part dimension (Eq. 1-4) include the surface area (S)-to-volume (V) ratio ($D_{part\_S/V}$), geometric mean ($D_{part\_geom-mean}$), arithmetic mean ($D_{part\_arith-mean}$) and maximum projected dimension (D_{part_max}). A weighted measure, D_{part} (Eq. 5), was found most suitable as representative of overall dimensions of a micro-part. The minimum part dimension was not considered here as the surface area-to-volume (S/V) ratio is already a measure that yields a characteristic dimension that is less than the smallest projected dimension.

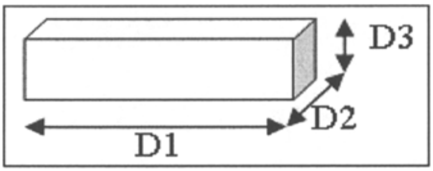


Fig. 4. Projected dimensions of piece part

$$D_{part\_S/V} = \frac{1}{(S/V)_{part}} \tag{1}$$

$$D_{part\_geom-mean} = \begin{cases} \sqrt[3]{D_1 D_2 D_3}, & 3D \text{ for description} \\ \sqrt{D_1 D_2}, & 2D \text{ for description} \\ D_1, & 1D \text{ for description} \end{cases} \tag{2}$$

$$D_{part\_arith-mean} = \begin{cases} \frac{D_1 + D_2 + D_3}{3}, 3D \text{ for description} \\ \frac{D_1 + D_2}{2}, \quad 2D \text{ for description} \\ D_1, \quad 1D \text{ for description} \end{cases} \quad (3)$$

$$D_{part\_max} = \begin{cases} Max(D_1, D_2, D_3), 3D \text{ for description} \\ Max(D_1, D_2), \quad 2D \text{ for description} \\ D_1, \quad 1D \text{ for description} \end{cases} \quad (4)$$

$$D_{part} = w_1 * D_{part\_S/V} + w_2 * D_{part\_geom-mean} + w_3 * D_{part\_arith-mean} + w_4 * D_{part\_max}, \quad (5)$$

where the weights w_1, w_2, w_3, w_4 are chosen by the user. Note that the sum of all weights is equal to 1.

It is useful to keep measures of the projected dimensions separately at a level further down in the hierarchy. Hence, a 3-digit code is used for the three projected dimensions. For the special primitive geometries, however, these three dimensions are chosen to help evaluate the surface area and volume. This helps maintain the relation between the projected dimensions and the evaluated characteristic part size.

Suitable ranges for part dimensions must be defined to carry out the coding. The ranges were calculated by carrying out a mathematical analysis of forces in micro-assembly combined with a statement-inference method for establishing critical dimensions [4, 7-11]. The force analysis was first carried out to evaluate gravitational, electrostatic, Van-der-Waals and capillary forces for a spherical part-planar surface system as described by Fearing [10] and Enikov [11]. Several simulations were run to predict forces by varying material properties of part and gripper, dielectric, distance between sphere and plane, contact angle and surface tension of liquid. The work was further extended to different geometrical primitives discussed earlier by using a measure for an equivalent spherical radius, r_{eq}, based on the surface area, S, as:

$$r_{eq} = 0.5\sqrt{\frac{S}{\pi}} \quad . \quad (6)$$

Based on the results of this force analysis and the statement-inference method, different ranges for coding the parts dimensions were established. For example, if $D_{part} < 1$ μm, the code assigned is 1, which takes care of sub-micron part and feature sizes and the dominance of Van-der-Waals force. For 1 μm $<D_{part}<$10 μm, it is found that this range is not very suitable for dry manipulation, and to identify this unique characteristic, the code assigned is 2. The next code 3 is assigned to parts in the range 10 μm – 100 μm to identify the range where electrostatic, capillary and Van-der-Waals forces have similar order of magnitude for many cases of simulations. For the range 500 μm – 700 μm, the code assigned is 6 and this helps identify the critical dimension above which metallic vacuum grippers are found suitable and also the range where gravitational force comes within one order of magnitude of the remaining forces. The remaining codes are assigned with a similar logic.

4.2 Part Material Code

The part material code is designed to provide information related to key material properties that influence the assembly process.

4th digit – Material

Part materials were classified broadly as metals, polymers, ceramics, composites and non-metallic minerals. This hierarchy was further broken down with metals split into ferrous and non-ferrous alloys, polymers into thermoplastic, natural and thermosetting, ceramics into electronic, constructional, natural, glasses, engineering and composites into natural, particulate, fiber and dispersion types. Simplifying the classification further finally yielded specific engineering materials such as plain carbon steel, PVC, silicone, graphite, etc. These materials in the last level were selected for developing the coding scheme. This classification along with coding in parentheses is illustrated in Fig. 5.

5th digit – Mass

Peschke et al. [12] mention that the behavior of the objects involved in handling operations is, to a great extent, determined by their weight. This changes as the size of the objects decreases, i.e., as the volume of an object reduces by the third power, the surface area decreases only by the second power. Consequently, the force affected by a part's weight decreases more steeply than adhesion forces caused by the surface area. If the size of an object decreases below a critical value, the weight-dependent force is insufficient for overcoming the existing adhesion forces. In micro-assembly, this can result in the object sticking to the gripper. This sticking would create problems in a system for automated assembly [12]. Hence, it is imperative to know the weight of a micro-part. To identify some critical masses, magnitude of gravitational force with the extreme densities of water and tungsten was tabulated for different geometries and part sizes. This yielded limits for deciding ranges for various codes. For instance, parts with a mass between 10^{-4} mg and 10^{-2} mg are given code 1, while heavy parts with mass greater than 100 mg are given a code 9.

6th digit – Specific Stiffness

Prusi et al. [13] mention that the stiffness of the micro-part is a possible factor affecting the success of a precision assembly work cycle. The Fraunhofer Institute in its 2000 annual report [14] mentions that a high specific stiffness and low specific weight of the micro-parts allows for high dynamics and low power consumption of the drives that actuate the positioning stages. Accordingly, specific stiffness, which is defined as Young's modulus divided by density (E/ρ), can be expected to play an important role in deciding micro-part handling and manipulation. On studying the specific stiffness of various materials, with units MNm/kg, it is found that certain types of materials fall in different stiffness ranges. For instance, rubbers generally give a value of less than 0.1 while ceramics fall in the range of 30-200. Likewise, polymers yield values in the range 0.1-10. These observations help develop a coding scheme where different ranges correspond to low, moderate and high stiffness values.

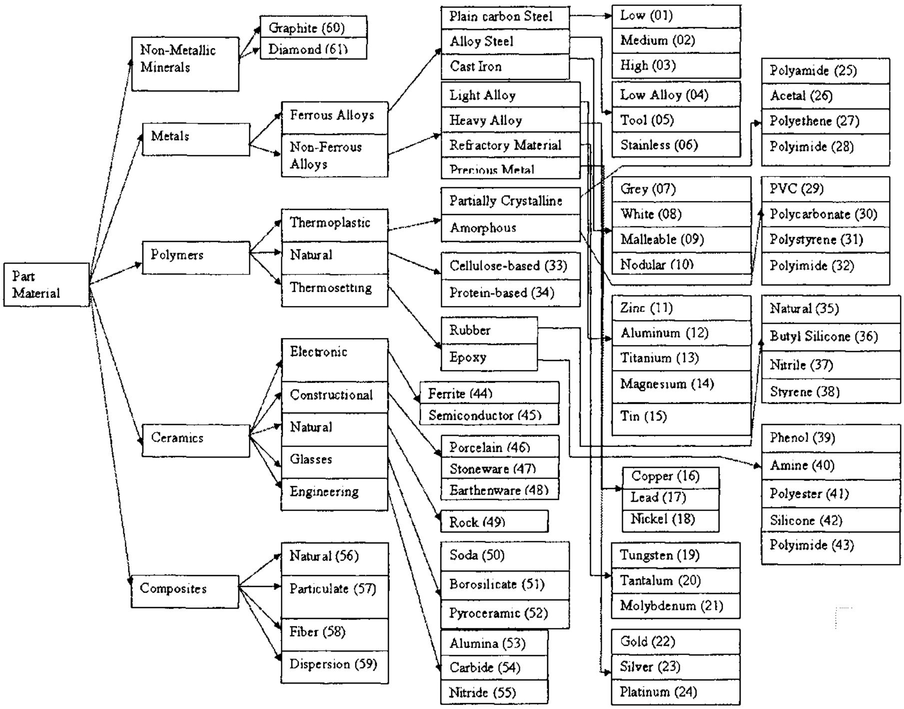


Fig. 5. Classification and coding of part material

4.3 Part Process Code

The part process code is included to provide important information that is related to the assembly process directly.

7th digit – Part Positioning and Alignment

This attribute describes the relative orientation of one part to another. It is based on the number of degrees of freedom required for alignment. It is further classified into coarse alignment techniques, viz., manual and external tool, and fine alignment techniques, viz., self alignment using surface tension, electrostatic force, magnetic force, external tool, separated constraint, and integrated constraint. The alignment directions and desired accuracy are also coded. All of these are stored at a level lower in the hierarchy.

8th digit – Surface Roughness

There are different measures for surface roughness. Of these measures, it was found that the average roughness, R_a is the most suitable measure for the coding scheme [15]. A non-dimensional ratio for coding the surface roughness can be defined as:

$$\Re^* = \frac{R_a}{D_{part}} \quad (7)$$

Here, $\Re^*$ is the relative surface roughness obtained by normalizing the average roughness with respect to the characteristic part dimension, D_{part}, which was defined by Eq. 5. For example, for a part with 1 Å average roughness and part dimension of 10 mm, $\Re^* = (10^{-10}/10^{-2}) = 10^{-8}$. On the other hand, although a part would never be expected to have roughness that exceeds its characteristic dimension, giving a limit of $\Re^* = 1$, some parts may actually have such a possibility since the characteristic dimension is evaluated taking all the dimensions of the object into account. Hence, a coding scheme for surface roughness can be defined as:

$$\square = ceil(-\log_{10}(\Re^*)) \quad (8)$$

Here, the function ceil(x) is defined as the smallest integer greater than x. With this coding, a $\Re^*$ value between 10^{-5} and 10^{-4} would yield a code 5. The codes vary from 0 to 9 covering $\Re^* \leq 10^{-8}$ on one end with a code 9 and $\Re^* \geq 1$ with a code 0 on the other.

5 Coding of Assembly

Several attributes of an assembly have been identified that are key to deciding the steps in the assembly process. Form, material and process codes relating to an assembly were formulated as discussed below.

5.1 Assembly Form Code

The assembly form code is required to provide key geometry-related information about the assembly, specifically, the number of different types of parts and the type of assembly.

1st digit – Distinctly different parts

For an assembly consisting of 'k' parts, part 'i' is considered distinct if either of these conditions is satisfied:

i) The geometrical shape of part 'i' is different from all parts 'j', where $j=1,2,\ldots,k$, $j \neq i$

ii) The *characteristic* dimension of part 'i' is different from all parts 'k' having same geometrical shape as 'i'.

2nd digit – Type of assembly

The type of assembly is often a decision that has to be made by the design engineer based on his experience of what is exactly needed for the application. This choice in turn influences the selections of assembly system elements. Several different types of assembly are identified such as pick-and-place, peg-in-hole, joining, sacrificial layer, etc.

5.2 Assembly Material Code

The assembly material code is required to provide information related to materials and their properties that directly affect the assembly process. It is seen that the most critical part imposes the maximum constraints on a successful assembly. Every new type of material necessitates specific decision taking with regards to its properties such as brittleness, ductility, yield strength, etc., which influence handling and other procedures related to the assembly of the piece part. The tolerance requirement on the most critical part determines the most stringent constraints in the manufacture and assembly of the piece parts. Similarly, the tolerance requirement on the most critical joint determines the most stringent constraints during the assembly process. The mass of the assembly determines the overall manipulation and packaging of the final assembly and is not necessarily the same as the mass of all the parts put together since there could be additional weight due to joining processes such as weld deposit, glue, etc. Further analysis is being carried out on these attributes.

5.3 Assembly Process Code

The assembly process code is required to provide process related information about the assembly. The assembly environment impacts the assembly process significantly in terms of selection of grippers such as vacuum grippers, electrostatic grippers, etc., which can work well only in specific environments. Important environment variables are assembly medium (vacuum, clean room, etc.), temperature and humidity. The surface properties of the assembly such as roughness and presence of external features such as chamfers, grooves, etc., determine its manipulation, visibility and packaging. A quantitative measure for this can be established based on an average taken on the surface roughness of the surfaces on the exterior. The codes can then be established similar to the code for surface roughness.

6 Example Application

One example of a micro-scale system/device family is the class of miniature bearings used in missile and space-craft guidance systems, e.g., spin bearings and gimbal bearings. Figure 6 shows the components of a miniature spin bearing assembly consisting of outer and inner races, a retainer and twelve balls. Each of the piece parts was analyzed to yield the part coding as shown in Table 3. All the parts have rotational symmetry giving a code 0 for the first digit. The balls are spherical with a code 1, while the remaining parts are close to cylindrical but not quite due to curvature and other features giving a code for irregular shapes, which is 9. Also, the inner race has dimensions: outer radius of 3486 μm, height of 2032 μm and inner radius 2977 microns yielding a characteristic dimension code of 898 corresponding to these three dimensions, explained in detail in Table 4. Corresponding dimensions for the outer race are 5164 μm, 2771 μm and 4615 μm, while for retainer are 4254 μm, 1981 μm and 3486 μm. It is seen that the races and retainer are fairly large and hence, gravity is expected to dominate. The balls are medium-sized with diameter 1587.5 μm giving a value for $D_{part\_S/V}$ of 264.58 μm and the remaining three measures for characteristic dimension as 793.75 μm. With equal weights of 0.25, the characteristic dimension is obtained as 661.45 μm. Hence, it might be important to take care of sticking effects. The races and balls are made of low alloy steel which corresponds to the code '04' as seen in Fig. 5, opening up the possibility of magnetic manipulation. The retainer is made of delrin with a low specific stiffness of 2.19 giving a code 3, and therefore, this part requires care in handling. The geometry of the retainer requires alignment for the balls to enter the holes. The directions of the alignment for the assembly process forms the first digit of the position-align code and is established from the assembly process as 0 for x-axis and 1 for y-axis, respectively, for the two degrees of freedom for the races and retainer. The coarse and fine alignment procedures give codes of 1 and 4, respectively for the retainer and the races. Similarly, the required accuracy of ~60 nm gives a code for the last digit of the position-align code as 2. Also, the inner race is manufactured with an average surface roughness specification of 60 nm, which gives a value of $\Re^*$ equal to 2.51×10^{-5}.

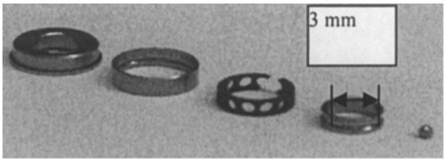


Fig. 6. Spin Bearing Assembly Components

The assembly code for this part was also developed as shown in Table 5. It was seen that this assembly is moderately complex with four types of parts, giving a code 4 for the first digit of the assembly code. An ad-hoc assembly type is required calling for a new innovative design (code 9). The balls are identified as the most critical part corresponding to a code '04' and can be considered for parallel manipulation due to their large number. It is a fairly heavy assembly weighing 724.27 mg (code 9) and gravity is going to dominate overall removing the need for any special manipulation for sticking effects while removing the assembly from the workspace.

Figure 7 shows the actual assembly design solution for the spin bearing. The assembly procedure uses a pusher which is used to push the inner race, which is fed from the magazine, into the central chamber. A plunger then comes down to force it onto the post. This centers the inner race. As the plunger pushes down, the inner race goes through a set of spring actuated doors that also help to center it. Similar steps are then repeated for the retainer. The only difference is the geometry of the pusher that helps align the retainer with respect to the ball feeder. Next, the ball feeder is raised to a pre-determined height. Then, balls load on their own by gravity feeding. With the help of external vibration or some similar external effort, the balls enter the grooves of the retainer. A cylindrical magnet at the bottom of the structure keeps the balls in place. Simultaneous with the lowering of the ball feeder the outer race is fed using the placer assembly. The outer race comes down to snap on to the remaining parts of the assembly. Next, the placer assembly is lifted up with the fully assembled spin bearing held in the doors. The plunger comes down to force out the assembled bearing.

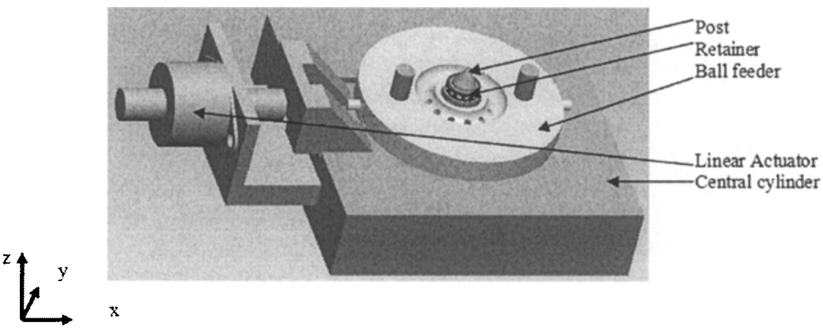


Fig. 7. Assembly of Spin Bearing

Table 3. Example coding of parts for miniature spin bearing assembly

Part	Description	Code	Characteristic Dimension Code	Position-Align Code	Inferences for assembly
Inner Race	Rotational symmetry (0); Irregular (9); D_{part} = 2391.4 μm (8); Low Alloy Steel 52100 (04); Mass = 135.55 mg (9); Sp. Stiffness = 26.15 (4); 2 DOF alignment, using magazine and pusher, plunger and doors (2); $\Re^*$ = 2.51x10^{-5} (5);	098049425	898	01421142	Fairly large size part; Gravity could be dominant; Possible need of tool control; Smooth part; At least one axis of rotation; Magnetic manipulation possible;
Outer Race	Rotational symmetry (0); Irregular (9); D_{part} = 3488.84 μm (9); Low Alloy Steel 52100 (04); Mass = 365.86 mg (9); Sp. Stiffness = 26.15 (4); 2 DOF alignment, coarse using placer and design constraint (2); $\Re^*$ = 1.72 x10^{-5} (5);	099049425	998	01421142	Large size part; Gravity dominant; Possible need of tool control; Smooth part; At least one axis of rotation; Magnetic manipulation possible;
Retainer	Rotational symmetry (0); Irregular (9); D_{part} = 2797.46 μm (8); Delrin (26); Mass = 26.42 mg (7); Sp. Stiffness = 2.19 (3); 2 DOF alignment using magazine and pusher, plunger and doors (2); $\Re^*$ = 2.14 x10^{-5} (5);	098267325	998	01421142	Fairly large size part; Gravity could be dominant; Possible need of tool control; Smooth part; At least one axis of rotation.
Balls	Rotational symmetry (0); Spherical (1); D_{part} = 661.45 μm (6); Low Alloy Steel 52100 (04); Mass = 16.37 mg (6) ;Sp. Stiffness = 26.15 (4); 2 DOF alignment using ball feeder and external vibration (2); $\Re^*$ = 9.07 x10^{-5} (5);	016046425	700	21525152	Medium size part; Electrostatic, adhesive, surface tension forces could be important; Possible need of tool control; Smooth part; Magnetic manipulation possible;

Table 4. Coding of part dimensions for miniature spin bearing assembly

Part	D1	D2	D3	Dpart_ S/V	Dpart_ geom	Dpart_ arith	Dpart_max	Dpart	Code	Characteristic Dimension Code
Inner Race	2976.88	3486.15	2032	165.88	2912.09	3001.43	3486	2391.39	8	898
Outer Race	4615.18	5163.82	2771.14	228.98	4196.30	4366.26	5164	3488.84	9	998
Retainer	3486.15	4254.5	1981.2	140.96	3297.67	3496.73	4255	2797.46	8	998
Balls	793.75	--	--	264.58	793.75	793.75	793.75	661.45	6	700

All dimensions are in microns

Table 5. Example coding of assembly for miniature spin bearing assembly

Sub-assembly	Description	Code	Inferences for assembly
Spin bearing	4 parts (4); New assembly technique (9); Most critical part – balls (low alloy steel) (04); 2 dissimilar materials (2);Tolerances – 60 nm (1,1);Mass = 724.27 mg (9); Assembly environment – clean room (0); $\langle \Re^* \rangle$= 7.68x10^{-5} (5);	4904211905	Moderately complex assembly; ad-hoc technique; magnetic manipulation possible; minimal influence of material properties; low tolerances; fairly heavy assembly; normal micro-scale assembly environment; smooth exterior

7 Conclusions

This paper has described a comprehensive framework for coding and classification for micro-assembly. Some of the key conclusions from this paper are:

i. Piece-parts for micro-assembly can be classified and coded using the proposed coding scheme for form, material and process parameters of the individual parts.
ii. The final assembly can also be classified and coded using the proposed coding for assembly attributes.
iii. Key steps in the assembly of a spin bearing are outlined by analyzing the codes for the individual parts and final assembly and linking them to the design process.

With continual pressures to reduce product life-cycle development times, this classification and coding system procedure can serve as a useful tool in the product design process as well as the process of designing/reconfiguring the micro-assembly system. Also, such a coding system can help quickly assemble and disassemble components in a reconfigurable assembly station where different types of grippers, manipulators, vision systems and force sensing equipment is available.

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