Development of Vibratory Part Feeder for Material Handling in Manufacturing Automation: a Survey

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Abstract:
In manufacturing automation, material handling plays a significant role. Material handling is the process of loading, placing or manipulating material. The handling of materials is to be performed efficiently, safely, accurately in a timely manner so that the right parts arrive in right quantities to the right locations, at low cost and without damage. The material handling devices are generally designed around standard production machinery and integrated with specially made feeders. In assembly and processing operations, there is a need for the parts to be presented in a preferred orientation, which is achieved using part feeders. A perfect example of feeders is vibratory feeders. Vibratory feeders are commonly used in industries for sorting and orienting parts before assembly. In this paper, a survey of literature regarding design and development of part feeders is discussed. The survey includes sensorless vibratory feeders to vision based flexible part feeders.

Keywords: *vibratory part feeder, flexible part feeder, conveying velocity*

1. Introduction

Part feeders play a vital role in manufacturing industries. A part feeder has three major functions: storing, aligning and feeding. Feeders are used to make the production faster, convenient and inexpensive. They are designed to supply a specific type of material, which is a part of the production process. They help in maintaining the flow of product needed for the next stage of the process. A part feeder intakes parts of arbitrary orientation and provides output in uniform orientation. Presenting the part in preferred orientation is very much useful in assembly and processing operations and this could be easily achieved through part feeders. Vibratory feeders are perfect examples of part feeders. Vibratory feeders are commonly used in industries for sorting and orienting parts before assembly [1]. The ease of controlling the flow of bulk materials and their adaptation for processing requirements make vibratory feeders, dearer among the manufacturing industries. Vibratory feeders provide suitable alternate to manual labour, thereby saving manufacturer's time and cost. Further, labour could be utilised for value adding activities rather than non-value adding activities such as segregating, stacking etc. Designing an industrial part feeder consumes more time and is a trial and error process. The designer has to take into account of some critical aspects such as part to be fed, number of parts, material of feeder etc. [2]. This paper deals with the survey of published works in the area of design and development of part feeding systems. Natural resting orientation of a part is the way in which the part could rest on a horizontal surface naturally [3]. Fore-knowledge of probability of feasible natural resting orientation of part is critical in developing an efficient part feeder [1], [4]. Hence, the literature survey on methods available for determining the probability of natural resting orientation of parts was the first step. Then, the literature on design and development of part feeding devices and flexible part feeding systems was done.

2. Determining the Probability of Natural Resting Orientations

The parts are to be oriented in desired manner for automated assembly operation [4]. If the most probable natural resting orientation of the part is chosen as the preferred orientation, the need to re-orient parts would be minimized. Most probable natural resting is the orientation which has the highest probability of occurrence. Greater the number of parts in preferred orientation, higher is the efficiency of the part feeder [1]. Ngoi *et al*. [5] stated that, components have to be fed and aligned in a proper orientation at high speed in automated assembly. They also emphasized that for continuous feeding of parts through vibratory feeding; the parts were to be fed in the most probable natural resting orientation. They determined the probability of natural resting orientations of parts using drop test.

Moll and Erdmann [6] focused on orienting parts with minimal sensing and manipulation. A new approach to orient parts through manipulation of pose distributions was elaborated. The pose distribution of a part being dropped from an arbitrary height on arbitrary surface was determined through dynamic simulation. They analyzed the effect of drop height and shape of support surface on pose distributions. They also derived a condition on the pose and velocity of a planar object in contact with a sloped surface, which enabled to determine the final resting orientation of the part. They also validated the dynamic simulation results with experimental results.

The experimental method to find the most probable natural resting orientation is time consuming and hence the industries have the necessity of mathematical models to predict them from their geometries [2]. The commonly discussed theoretical methods in literature, to determine the probability of natural resting orientation of parts are energy barrier method, centroid solid angle method, stability method and critical solid angle method. The methods are discussed as follows:

2.1. Energy Barrier Method

This method was proposed by Boothroyd *et al.* [3]. The probability of a part to come to rest in a particular orientation is a function of the energy tending to prevent a change of part orientation and amount of energy possessed by the part when it fall into that resting orientation. For complex parts with more than two natural resting orientations, this method was difficult to compute the energy barrier and hence only preferred for simple parts with constant cross section and two natural resting orientations [2].

2.2. Centroid Solid Angle Method

This method was proposed by Lee *et al.* [7]. A solid angle is defined as one steradian unit subtended by a part of the spherical surface whose area equals the square of the radius of the sphere. The centroid solid angle is the solid angle subtended from the centroid of a part. The centroid solid angle method is based on the assumption that the probability of a component resting on a specific orientation is directly proportional to the magnitude of the centroid solid angle and inversely proportional to the height of its centroid from that orientation.

The following steps were followed to determine the solid angle of the parts:

1. Assume the part is resting on a flat surface in any orientation.
2. Locate the centroid of the part (Figure 1).
3. Construct a pyramid with centroid as the apex and base of the part (Figure 1).
4. Construct a sphere of any arbitrary radius (R) with the centroid as its centre. The radius of sphere should not exceed the part height. (Figure 1).
5. The intersected volume of pyramid and sphere is called the enveloped volume, from which centroid solid angle can be found (Figure 2).

The centroid solid angle of that orientation (W_i) is computed by,

$$W_i = Surface\ Area/R^2 \qquad (1)$$

If a part has 'n' natural resting orientations, then the probability of natural resting orientation is obtained by Equation (2),

$$p_i = \frac{\frac{W_i}{h_i}}{\sum_{j=1}^{n}\frac{W_j}{h_j}} \qquad (2)$$

- p_i is the probability of the part resting on orientation 'i',
- n is the number of natural resting orientations,
- W_i is the centroid solid angle subtended by orientation 'i' from centroid, sr,
- h_i is the height of the centroid from orientation 'i', mm,
- W_i is the centroid solid angle subtended from centroid by 'j', sr,
- h_j is the height of the centroid from orientation 'j', mm.

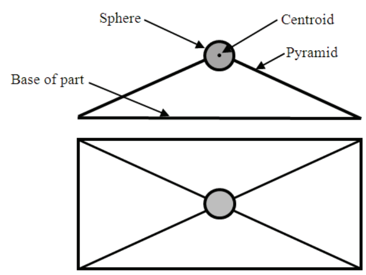

Figure 1. Creation of pyramid with centroid as apex

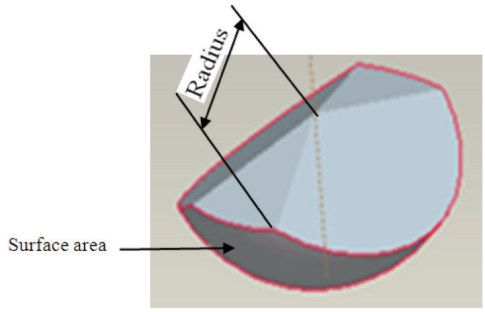

Figure 2. Solid angle generation

The set of these probabilities is called Static Probability Profile.

2.3. Stability Method

Stability method is based on logical analysis and was elaborated by Chua and Tay [8]. Larger the contact area with the base more is the stability. Similarly, if the center of gravity of the part is much lower and nearer to the base, stability is higher. The stability method is based on these two aspects. Stability 'S' is a function of the magnitude of the contact area (Ar) and the distance of the center of gravity(y) from the base. 'S' is proportional to 'Ar' and inversely proportional to 'y'. The generalized equation is given by Equation (3).

$$p_i = \frac{\frac{N_i Ar_i}{y_i}}{\sum\frac{N_i Ar_i}{y_i}} \qquad (3)$$

- p_i is the probability for the orientation 'i',
- N is the number of surface identical to and inclusive of the contacting surface,
- Ar is the contact area, mm^2,
- y is the distance from base to center of gravity, mm.

2.4. Critical Solid Angle Method

This method is based on the hypothesis that the probability of a part to rest in a particular orientation is proportional to the difference between the centroid solid angle subtended by that orientation and critical solid angle of that orientation for changing to rest in its neighboring orientation and is inversely proportional to the height of centre of gravity of that orientation [9]. The Critical solid angle is the solid angle subtended by the resting orientation of the part, with respect to the point that lies on the line normal to that orientation and passing through the centre of gravity, at the height of the length between the centre of gravity and the edge of that orientation and its neighboring orientation. The solid angle at a critical position of the part that is least required for the change in orientation of the part (with the part resting on its edge) is termed as critical solid angle. Whenever the part tries to shift its position to any one of the neighboring orientation, a new critical solid angle is available. Hence, the probability that a part comes to rest is proportional to the difference between the centroid solid angle subtended by that resting orientation and average of the critical solid angles of that orientation when trying to shift to its neighboring orientations and inversely proportional to the height of center of gravity from that orientation. The probability of occurrence of each orientation is given by Equation (4).

$$p_i = \frac{\left(\frac{1}{m_i}\right)\sum_{ki}\sum_{ji}\left(\frac{\Delta Q_{ij}}{ht_i}\right)}{\left(\frac{1}{m_1}\right)\sum_{k1}\sum_{j1}\left(\frac{\Delta Q_1}{ht_1}\right)+\left(\frac{1}{m_2}\right)\sum_{k2}\sum_{j2}\left(\frac{\Delta Q_2}{ht_2}\right)+\cdots+\left(\frac{1}{m_n}\right)\sum_{kn}\sum_{jn}\left(\frac{\Delta Q_n}{ht_n}\right)} \tag{4}$$

Udhayakumar *et al.* [10] determined the most probable natural resting orientation for a family of sector-shaped parts using drop test and theoretical methods (Centroid solid angle method, stability method and critical solid angle method). The effect of initial orientation of the part during drop and height of drop, on the natural resting orientation, was also studied [11]. Pearson's χ^2 test for goodness of fit between the drop test and theoretical method results revealed that the null hypothesis could not be accepted at 95% confidence level.

The next section provides the literature survey in the area of part feeders.

3. Vibratory Part Feeders

This section deals with the literature related to design and development of part feeders. About 50% of manufacturing cost and 40% of workforce is dedicated to production assembly [12]. A part feeder intakes identical parts of arbitrary orientation and provides output in uniform orientation. In assembly process, the parts were to be shifted from one orientation to another and the most humanoid way of doing that was gripping the part and then shifting it to another orientation [13]. Vibrating feeders are commonly used in industries for orienting parts. Vibratory part feeders are more commonly used in industries such as food processing, plastic component manufacturing, automobiles etc. The most important factor to be considered when selecting a part feeder is the type of parts to be fed. Feeder sizes and types are determined through a variety of factors such as: part size and configuration, part abrasiveness, condition of the part when handled and the required feed rate. The design of industrial parts feeders is trial and error process that can take several months [2].

Berkowitz and Canny [14] developed a tool to test the feeder designs. The behavior of the system was evaluated using Markov model. The probability that a part in any random orientation ends up in a desired/preferred orientation was computed using Markov analysis. The probability of each pre and post orientation that a gate will convert was computed and based on that, the efficiency was calculated. They used the developed tool to simulate a feeder with edge riser. They concluded that future work was required to determine the accuracy of simulation results on actual feeder.

Lim [15] performed the dynamic analysis of the vibratory feeder. A theoretical analysis of feeding on a track vibrating with simple harmonic motion was presented. Based on his analysis, the factors affecting the conveying velocity of part on a vibratory feeder are excitation frequency, amplitude of vibration, coefficient of friction and track angle. A model was developed to predict the conveying velocity based on the above said factors. The results of the developed model followed the same pattern as that of the experimental results.

The part motion on a planar part feeder which had a longitudinally vibrating flat plate was discussed by Reznik *et al.* [16].They stated that feed rate was due to plate motion in forward motion for a longer time than backward motion combined with non-linear nature of Coulomb friction. They developed analytical expressions for feed rate. Though the analytical results deviated from rigid body dynamic simulation results, they followed the same pattern.

Many methods of sensorless part feeding were discussed in literature that includes orienting and positioning using push forces, fences etc. Akella and Mason [17] discussed the use of pushing action for orienting and translating objects. In their paper, the following were briefed:

1. The sequence of linear normal pushes for orienting and positioning polygonal objects
2. Existence of sequence of linear normal pushes to move any polygon from start pose to goal pose
3. Polynomial-time pose planner that generate push sequence to orient any polygon to the goal pose.

Beretty *et al.* [18] demonstrated that a polygonal part could be oriented using fences placed along a conveyor belt. At the end of conveyor, a part of any pose could be converted to unique final pose using fences. They developed an algorithm for developing a fence design of minimal length (i.e. less number of fences). The results proved good to fence designs for parts with acyclic left and right environments. But, they could not be generalized for any arbitrary parts.

Lynch [19] augmented a 1JOC (Joint Over Conveyor) with a prismatic joint that allows the fence to move vertically and hence named them as 2JOC. They attempted feeding of 3D parts on the conveyor by combining toppling with the ability of the 1JOC to perform conveyor-plane feeding. He also proposed the idea of developing inexpensive part feeders using toppling and pushing actions. He also derived the mechanical conditions for toppling.

Bohringer *et al.* [20] developed a programmable equipment that used vibrating surface for positioning and orienting parts without sensor feedback or force closure. This was based on dynamic modes of vibrating surface. They explained the apparatus using planar objects. They also developed polynomial-time algorithms to generate sequences of force fields.

Manipulating a planar rigid part on a conveyor belt using a robot with just one joint was explored by Akella *et al.* [21]. Their approach provided a simple and flexible method for feeding parts in industries. The 1JOC approach used a fixed velocity conveyor along with a single servoed joint to obtain the diversity of motions that were required for planar manipulation. They also proved the 1JOC is capable of useful planar manipulation: any polygon is controllable from a broad range of initial configurations to any goal chosen from a broad range of goal configurations. They demonstrated that the sensorless 1JOC could position and orient polygons without sensing.

Berretty *et al.* [22] discussed a sequence of mechanical devices such as wiper blades, grooves to filter polygonal parts on a track. They termed this as 'traps'. They discussed several gates of trap such as balcony, gap, canyon, and slot. They have a series of mechanical barriers (also known as gates) which either reject the disoriented parts or reorient the parts to desired orientation. The former type is known as passive trap and the latter as active trap. Active traps are preferred than passive traps, since the efficiency of active trap is 100%. These traps are mounted at the exit of the vibratory feeder. Vibratory bowl feeders are suitable for smaller parts whereas liner vibratory feeders can be used for handling larger parts. Active devices convert any orientation of the part to the desired orientation whereas passive devices reject the disoriented parts. The sequence of placement of passive and active devices depends on the orientation to be obtained as output.

Wiendahl and Rybarczyk [23] presented the possibilities and the potentials of aerodynamic part feeding processes. They used the idea of aerodynamic part feeding, e.g. a permanent air field which forced apart into the desired orientation without the need for any control by sensors. They elaborated on three different aerodynamic part feeding methods. The orientation method was based on the behavior of workpieces in a field of air flow. Usable part characteristics for this method were the general air resistance and the center of gravity. The tipping method was applied for the orientation of the workpiece with the axis of rotation parallel to the direction of transport. The part characteristics were local air resistance, projected shape and the center of gravity. The rotating method was developed for the orientation of the workpieces with the axis of rotation vertical to the direction of transport. The possible part characteristics were air resistance, center of gravity and projected shape.

Jiang *et al.* [24] developed a 3D simulation software for parts feeding and orienting in a vibratory bowl feeder. A mathematical model of part motion and its behavior in orienting mechanism was determined. Based on the model, a 3D simulation software was developed using Java. The computer simulation results had a good agreement with the experimental results.

Force analysis and dynamic modeling of a vibratory feeder was presented by Richard *et al.* [25]. The vibratory feeder was equated to a three-legged parallel mechanism and geometric property of the feeder was determined. The effect of the leaf-spring legs were converted to forces and moments acting on the base of the bowl. A dynamic model that integrates the angular displacement of the bowl with the displacement of the leaf-spring legs was developed. Newtonian and Lagrangian approaches were used to verify the model

Goemans *et al.* [26], [27] introduced a new class of geometric primitives, called blades, to feed sensorics class of 3D parts by reorienting and rejecting all but a desired orientation. The blade received identical polyhedral parts in arbitrary orientation as input and outputs parts in one single orientation. The blade is nothing but a horizontally mounted convex polygonal metal plate attached to the feeder wall. This plate was parallel to the track and had a triangular shaped segment and a rectangular shaped segment. The three parameters to characterize a blade were blade angle, blade height and blade width.

Vose *et al.* [28] used force fields for sensorless part orientation. They developed large family of programmable frictional force fields by vibrating the rigid plate. They also stated that the strength of field and line of squeeze line were easily controllable in six degree of freedom implementation.

Ramalingam and Samuel [29] investigated the behavior of a linear vibratory feeder, used for conveying small parts. A rotating drum with radial fins was designed and developed for carrying out the experiments. A tumbling barrel hopper was developed for feeding the components onto the track. They considered the parameters affecting the feed rate and conveying velocity of part such as barrel dimension, amplitude and angle of vibration, coefficient of friction and the operating frequency and the influence of these parameters was determined experimentally.

Three different types of sensorless part feeding devices for handling asymmetric parts was discussed by Udhayakumar *et al.* [30]. They inferred that the efficiency of feeder increases with number of passes. They determined the effect of excitation frequency and amplitude of vibration on velocity of part on a vibratory feeder. A model to determine the velocity of part was also presented.

A trap based vibratory part feeder for conveying brakeliners was developed by Udhayakumar *et al.* [31]. The trap had an efficiency of 100%. An expression relating the conveying velocity of part as a function of excitation frequency, vibration amplitude and trap inclination angle was obtained through regression analysis. The developed set-up was able to reduce the time taken for stacking 80 parts by 13.5%.

To investigate the dynamic behavior of the feeding part, a 2D numerical model based on discrete element method was developed by Ashrafizadeh and Ziaei-

Rad [32]. The feeding part was assumed as rectangular shape with three degrees of freedom. Through simulation, a good agreement between the calculated and experimental data was observed. They concluded that co-efficient of friction had a critical role in sliding regime but not in hopping regime. The proposed model was capable of demonstrating the periodic and chaotic behavior of the part.

A novel vibratory feeder called Decoupled vibratory feeder (DVF) was discussed by Linag *Han et al.* [33]. In DVF, excitation is provided in two mutual perpendicular directions. The governing parameters such as vibration angle, excitation frequency, and waveform of driving signals and phase angle between vertical and horizontal excitations were adjusted through software. They also developed a test system to evaluate electromagnets performance.

Prediction of appropriate parameters for conveying brake pads on a vibratory feeder was discussed by Suresh *et al.* [34]. They determined the optimal frequency, trap and track angles using linear regression model.

4. Flexible Part Feeders

This section includes literature on non-vision based and vision based flexible part feeding systems. Boehlke *et al.* [35] stated that 50% of failure in automation systems attribute to custom built vibratory feeder. Janeja and Lee [36] stated that if the existing orienting elements were able to be adjusted rapidly, then this would convert a rigid design to a flexible one without any sacrifice in its efficiency. This would be able to handle a family of similar parts. Flexible feeders have the capability to accommodate most of the parts of one or more family, with minimum changeover time [37]. The flexible part feeders can be generally classified in to the following two classes:

1. Feeders that are non-vision based and rely on simple sensors or reconfigurable gates to handle the parts of one or more family.
2. Vision based feeders that depend on vision cameras to handle the parts of one or more family.

4.1. Non-vision Based Flexible Part Feeders

The concept of using a LED (Light Emitting Diode) sensor to determine the part orientation was presented by Akella and Mason [38]. A LED sensor was used to measure the resting diameter or width of polygonal parts. An array of LEDs was arranged on the side of conveyor and a set of photo resistors on the opposite parallel side. By the LED-photo resistors blocked by the part, the resting diameter or width of polygonal parts was identified. Based on this partial information from the sensor, a robot was programmed to execute a sequence of push-align operations to orient the part.

Sim *et al.* [39] stated that programmable part feeders that can handle parts of one or more part families with short changeover times are highly in need. The capability of neural network based pattern recognition algorithm for recognition of parts was developed. Three fiber optic sensors mounted on vibratory bowl feeder were used to scan the surface of each feeding part. The scanned signature was used as input to neural network models to identify the part.

Tay *et al.* [37] developed a flexible and programmable vibratory bowl feeding system for use in a flexible manufacturing system. The feeding system was capable of identifying the orientation of non-rotational parts and re-oriented them into desired orientation. It was equipped with programmable passive and active orienting devices which allowed them to handle variety of parts. Nine specially designed stations were present along the track of the feeder for feeding of non-rotational parts. These stations were controlled by both the computer sub-system and PLC (Programmable Logic Controller) sub-system. The orientation of the part was identified using neural networks. Optical sensors were used to identify the internal features such as holes and pockets. Three types of neural network architectures were tried for pattern recognition and classification of feed orientation of parts in the feeder.

Chua [40] stated that the flexibility of assembly system is critical for survival in competitive manufacturing market. He also discussed the need for feeding system to handle asymmetric parts with high efficiency. He developed a part feeding system to handle cylindrical parts of different aspect ratios. His system included a singularity unit, V-belt orientator, transfer mechanism with aluminium plate and an unloading module with delivery chute and re-orientation.

Udhayakumar *et al.* [41] developed an adaptive part feeder for handling sector-shaped parts. This feeder was able to accommodate a family of sector shaped parts. Capacitive sensors were employed to determine the size of part. Based on the size of the part, the feeding system was modified accordingly, to convey the part. A regression model was developed to determine the conveying velocity based on excitation frequency and amplitude of vibration.

A part feeding system based on piezoelectric vibratory conveyors was developed by Urs Leberle and Jürgen Fleischer [42]. Different variety of parts, including very delicate parts, could be fed in this conveyor. The design and commissioning of the conveyor set-up was discussed.

4.2. Vision Based Flexible Part Feeders

Causey *et al.* [43] presented the design and development of a flexible parts feeding system. He proposed three conveyors working together. The first inclined conveyor was used to lift parts from a bulk hopper. From the first conveyor, the parts were transferred to a horizontally mounted second conveyor. An under lit window presented a silhouette image of the parts to vision system. Based in this, the pose of part was determined and a robotic arm was used to acquire it. Parts in inferable orientation/overlapping were returned to bulk conveyer by a third conveyor. The guidelines for improving a part feeding system's performance were discussed.

Gudmundsson and Goldberg [44] analyzed the use of vision cameras in robots for part feeding. They found that the throughput of a part feeding system could be affected by starvation, where no part is visible to the camera and saturation (too many parts are visible to camera which acts as an obstacle for the robot to identify the part orientation and grasp it).

Chen *et al.* [45] developed a smart machine vision system for inspection of solder paste on printed circuit boards (PCB). Machine vision was considered since it has advantages over the traditional manual inspection by its higher efficiency and accuracy. The proposed system included two modules, LIF (Learning Inspection Features) and OLI (On-Line Inspection). The LIF module learnt the inspection features from the CAD files of a PCB board. The OLI module inspected the PCB boards online. The accuracy of detection has exceeded 97%, when deployed in the manufacturing line.

Sumi and Kawai [46] proposed a new method for 3D object recognition in a cluttered environment, which used segment-based stereo vision. Based on the position and orientation of the object, a robot was signaled to pick and manipulate it. Different shaped objects (planar figures, polyhedra, free-form objects) were tried for demonstration of the concept.

Khan *et al.* [47] used a vision set-up to inspect for defects based on the size, shape, color and dimensions of the part that arrived on a conveyor. The camera was mounted on the conveyor belt. Based on the output from the vision system, a lever attached to a stepper motor directed the part to the accepted or rejected trays. The accuracy of the system was found to be about 95%.

An overview of vision based system was discussed by Han *et al.* [48]. He stated that conventional part feeders were effective for specific type of parts, but had limitations where families of part (similar in shape but vary in size) were to be handled. He described the current design and retooling of feeder as a black art. A vision based vibratory feeder, where the major feeding parameters such as vibration angle, frequency, amplitude and phase difference could be adjusted online by software, was developed. The system was capable of handling wide range of parts without retooling. The best operating frequency was determined automatically though frequency response analysis. It was also capable of eliminating the parts jamming.

Mahalakshmi *et al.* [49] stated that 'Template matching' has created a revolution in the field of computer vision and has provided a new dimension into image processing. They have discussed the significance of various algorithms of template matching technique.

Flexible vibratory feeding system based on vision camera was proposed by Liang Hana and Huimin Lib [50]. The developed system was capable of identifying the part with preferred orientation. Otherwise, the part is again sent to the bowl. Auto vision software was used to identify the parts.

5. Conclusions

Automation is growing at a rapid pace in today's world. Having understood the significance of automation for success and growth of the industrial set-up, many companies are investing in bringing the latest technologies for the processes. Factory automation aims at minimization of manual and personnel related work over industrial, production and manufacturing processes. Vibratory feeders are suitable for feeding parts for subsequent processes on special machines in mechanical, electrical, pharmaceutical, bearing, optical, fastener and many industries. This paper focused on the various literature regarding the design and development of vibratory part feeders. The scope of survey included identifying the most probable natural resting orientation to the development of flexible part feeders. From the literature survey, it could be understood that many more advancements could be made in vibratory part feeding technology so that the feeders are extremely flexible as well as cheap. Further research could be focused on flexible part feeders that can handle a variety of parts without retooling, at an optimum feeding rate. The conveying velocity of the parts on the feeder should be predictable in order to maintain continuous flow. More research work is required in the development of predictive models to determine the conveying velocity and hence part behavior on part feeders are to be studied extensively.

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