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Design of a Flexible and Agile Centering Preprocessing System

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Abstract: Precise machining of bearing rings is integral to finished bearing assembly quality. The output accuracy of center-based machining systems such as lathes and magnetic chuck grinders relates directly to the accuracy of part centering before machining. Traditional tooling for centering on such machines is subject to wear, dimensional inaccuracy, setup time (hard tooling) and human error (manual centering). A flexible system for initial part centering is proposed based on a single measurement system and actuator. In this system, the part is placed by hand onto the machine table, automatically rotated and measured to identify center of geometry offset from center of rotation, then moved by a series of controlled manipulations to align the centers. Such a system eliminates the need for part-specific tooling or the inconsistency of manual centering by a skilled operator, reduces the lifetime cost, and creates agility for varied part acceptance with minimal setup effort. Results in both time and accuracy are currently equivalent to the manual process.

1. Introduction

Currently, rotating bearing rings are manually centered prior to measurement by a skilled operator using a brass hammer. This method is both expensive due to cost of skilled labor and inconsistent due to repeatability and reproducibility error. For less massive parts within the range being considered, 0.5kg-70kg, some parts can take more than 5 minutes to be centered within the 2.5µm required tolerance.

Automating this centering process reduces the variability both in achievable tolerance and centering time. Agility is maintained as with the manual process, but as the capitalized cost can be amortized over the expected lifetime, this solution gives a lower specific operating cost in addition to the reduction in variability. This solution also avoids the use of type-dependent hard tooling, which lacks flexibility.

2. Process Automation

The current manual approach of impact centering with the operator as the feedback mechanism was considered as the model of the automated system. The heuristic abilities of the operator to read ring position data from an LVDT, select the proper hammer to use, and properly plan the strike must be modeled and implemented into the automated system. Both measurement and path planning do not pose as much of a challenge as design of the proper interaction between the actuator and the part in order to affect the desired distance. One primary focus of the project is in *actuation planning*, both by pushing and by impact, to maintain the system agility.

2.1 Literature Review

2.1.1 System Agility

Agility defines the ability of a manufacturer to be successful in the face of change. Not only must a system be robust to noisy disturbances, but it must also be able to recognize and take advantage of opportunities through manufacturing flexibility [1]. As the whole system must be capable of quick response to change, this capability must also extend down to the manufacturing plants, cells, machines, and individual machine components. Lee particularly stresses the reconfigurability of material handling and fixturing [6].

Of particular interest is agile *fixturing*, which allows for acceptance of a variety of workpieces with minimal system reconfiguration. Li et. al. point out the type-dependent methodology and lack of fixture reconfigurability in current designs [7]. Newman et. al. address these issues through custom fingers on a common grip base, but admit that their own agility constraints are not met by this design method [11]. Guiding and locating of workpieces in an adaptable environment (i.e., without part-dependent tooling) is needed to achieve machine-level agility [2]. Of central importance to this flexible part location is an understanding of part manipulation strategies.

2.1.2 Manipulation by Pushing

Pushing has long been available as an alternative to the classical robotic pick-and-place strategy, particularly for bulky or heavy objects where lifting becomes infeasible. Mason initially analyzed the friction mechanics of planar sliding objects [10]. Peshkin and Sanderson have extended the analytic results on 3-degree of freedom sliding manipulation systems indeterminate of the supporting pressure distribution [12].

Examples of pushing as a cheap and flexible alternative form of manipulation have been demonstrated in the literature. Lynch and Mason have identified constraints for stable pushing directions, where the part maintains contact with the manipulator, and have used this information for motion path planning of polygonal objects [9]. Lynch furthered this analysis for multiple-point contact [8]. Another example is force-controlled pushing of static objects on a microscale by Zesch and Fearing [15]. The information regarding planar push strategies for geometrically regular objects can be directly applied.

2.1.3 Manipulation by Impact

Impact manipulation, whereby kinetic energy is transferred in a relatively short time from a striking object to a receiving object, is also applicable to this research.

Rigid-body impact is classically modeled in one dimension by Newton's kinematic impact law:

$$\varepsilon(v-V)=(C-c)$$

$$\varepsilon \equiv coefficient\ of\ restitution$$

$$V,v \equiv Body\ 1,2\ velocity\ before\ impact$$

$$C,c \equiv Body\ 1,2\ velocity\ after\ impact$$

This equation is a derivation of the one-dimensional conservation of linear momentum, with the assumption of a lumped energy-dissipative contact process as captured by ε.

Huang, Krotkov and Mason have used impact models to plan the manipulation of sliding objects [3]. In this case, the problem is broken into the *Inverse Sliding Problem*, where the required velocities to send a friction-damped object to a desired position are determined, and the *Impact Problem*, which determines the characteristics of the impact that will generate those velocities. Huang and Mason also discuss limiting cases of this research [4] and its application to robotic motion path planning and control [5].

Yao, Chen and Liu specifically explore the coefficient of restitution from the standpoint of energy conservation [14]. They determine an expression for the energetic restitution coefficient based on initial conditions (relative velocities and orientations). This research extends the previous finite-element modeling work of Zhang and Vu-Quoc [16].

2.2 System Description

The proposed automated centering system is based upon the manual method, specifically in application of an actuating force on the rotating ring at such a point and manner as to drive its geometrical center to the spindle's center of rotation.

The prototype system consists of a fixed air-bearing spindle upon which the subject part is placed, and a linear motor air-bearing slide which carries both a measuring probe for gauging the part surface and a pusher tip for actuating the part to align center of geometry with center of rotation.

System operation is an iterative process of planned actuations with the goal of aligning the centers of part geometry and rotation within a certain envelope tolerance (2.5μm for prototype testing). The basic process steps are

- *Rotate and follow part*
  The spindle is rotated at a constant velocity and the measurement probe deviation from a null value used to command the slide velocity. The slide follows the part contour, and contour data is written to memory.
- *Determine error vector*
  Data collected from the measurement probe and spindle encoder is used to determine the off-center distance and direction relative to the spindle angle.
- *Move part to align centers*
  The slide is moved at the proper time so as to actuate the part and align the centers through single point contact of the pusher tip against the part.

The major system components are pictured in Figure 1. The subject part is held by gravity to a plate with 3 carbide rails. The pusher tip and measuring probe are currently separate to allow for tip material prototype testing. However, the final configuration is planned to have the measurement probe and push tip in-line to allow for variation in subject part wall contour.

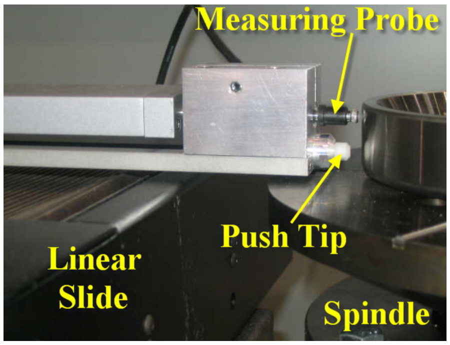

Figure 1 - Centering System Components

The agile centering system involves high-speed data collection, motion control with a high rate of change of the input signal, and path planning for impact. Each of these system features requires the ability to relate to one another on an absolute time base. For instance, if data collection and path planning are not synchronized, impact can occur at a suboptimal point, possibly degrading the system state rather than improving it. For this reason, the system has been implemented on a platform designed to minimize *jitter* (variation in the time base from loop to loop) and synchronize independent looping tasks (known as *threads*) on a common bus trigger, allowing relation of operations with respect to an absolute time scale.

3. Implementation

The proposed centering system software is realized on a prototype test station comprised of a National Instruments PXI-8145RT embedded system controller with a PXI-7350 multi-axis motion control board commanding the linear slide and spindle through third-party signal amplifiers. The PXI open standard (PCI eXtensions for Instrumentation), introduced in 1997, is an architecture that combines the current standard PCI bus with specialized synchronization buses accessible by LabVIEW Real Time software [13]. The system can run independently of a host PC, but in this project a PC is employed to allow for user interaction.

3.1 Algorithm Design

The algorithm is executed in a parallel loop structure using the LabVIEW Real-Time Module. LabVIEW is designed for multithreaded tasking and prioritization with integrated time and memory management for deterministic behavior.

The implemented algorithm consists of separate WHILE loops that execute independently and with known frequency (see Figure 2).

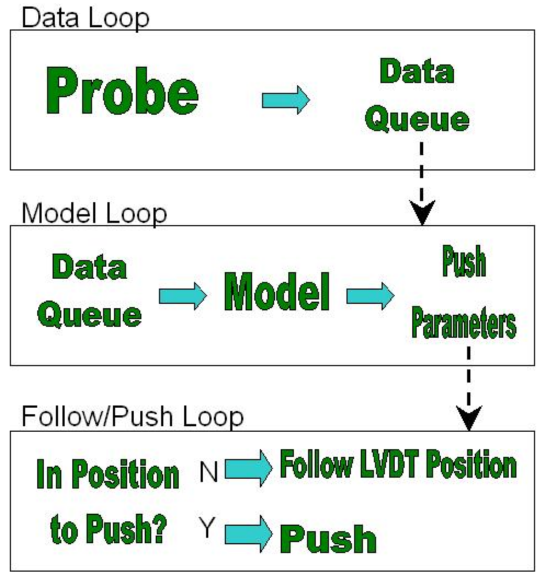

Figure 2 - Algorithm Parallel Loop Structure (Communication Loop not shown)

The tasks performed are

- *Data Collection (LOOP1)*
  The position of the measurement probe tip is simply calculated as the difference between the probe signal and the slide encoder signal. Data is logged relative to spindle angular position and stored in on-board memory. The queue is time-based, but its size is varied with spindle angular velocity to capture one point per degree rotation.

- *Data Modeling (LOOP2)*
  Once the data queue is filled with data of a single spindle rotation, the data are fitted to a single sine wave model with a period corresponding to a single spindle rotation. Through this calculation, the single-period frequency is extracted from the signal. The model is of the form

  $$y = b_0 + B\cos(x - \phi)$$

  expanded to

  $$y = b_0 + b_1\cos(x) + b_2\sin(x)$$

  After determining coefficients b_i through a linear least squares fitting routine, the off-center distance and direction (B and ϕ respectively) are found by

$$B = \sqrt{b_1^{\ 2} + b_2^{\ 2}}$$

$$\phi = \tan^{-1}\left(\frac{b_2}{b_1}\right)$$

This loop also calculates the required lead angle L at which to begin actuation in order to contact the part in the corresponding pushing direction ϕ.

- *Servo Following (LOOP3a)*
  The measurement probe at the end of the actuation arm commands the linear servo motor velocity through a simple PID scheme with a loop rate of 100Hz.

- *Actuation (LOOP3b)*
  When the actuation parameters B and ϕ have been determined for the current configuration, the actuation cycle is triggered by the spindle position crossing the trajectory lead position. In this case, LOOP1 following is suspended, and the slide undergoes a trapezoidal velocity profile of a given acceleration and peak velocity. This profile is designed to contact the ring with the pusher tip and align the centers. After movement is complete, the data queue is cleared and servo control returned to the following function.

- *Communication with Host PC (LOOP4)*
  The compiled program runs directly on a compact PXI remote system. The interface on the host PC must exchange user input and output with the system. This exchange is accomplished with a low-priority loop that can be preempted by any of the preceding loops, allowing communication to take place during idle periods and preventing interference with more critical tasks.

3.2 Determinism

A main benefit of the real-time system with synchronization is a high degree of *determinism*, the ability to complete an operation within a known fixed amount of time. This property allows separate threads, such as servo following control and data collection, to occur with known time intervals between them, allowing for prescribed actions to occur at the proper time.

The prioritization feature allows prescription of process importance, allowing critical processes such as motion control commands to preempt noncritical processes such as host screen updating. In this project, the data collection and following loops are given priority over the data modeling and communication loops, which are not as critical in absolute time.

3.3 Manipulation: Impact v. Pushing

Actuation of the part to be centered falls within 2 regimes: coarse centering and fine centering. The definition of coarse centering encompasses the gross movements required to move the ring from its initial placement position (up to 25mm off-center) to a position nearer to center. Though difficult to absolutely define, this transition is important from the standpoint of actuation strategy.

Coarse actuation requires the part to move a distance of up to 25mm. Applying a push actuation (pusher maintains contact) to move the part 25mm at a relatively rapid push velocity of 400mm/s would require contact of the pushing tip and moving part surface for 63ms. In experiment, it is found that such a long contact time allows for frictional interaction of the pusher tip on the part surface. This tangential force can overcome the static friction force, causing the part to move in an unstable manner rather than the pusher tip providing completely normal force (part "rolls around" pusher tip). For this reason, the actuation during coarse part centering is undertaken as an impact actuation, characterized by higher velocities and low contact time. This impact, coupled with trajectory planning, allows for minimization of the tangential force effect.

For fine actuation, actuation distance is greatly decreased. In this situation, application of impact can sometimes produce unwanted results as the final tolerance is neared. Impact can be so light as not to overcome the static friction force, producing a zero-distance movement. Alternatively, after the static friction force is overcome, the required force to maintain velocity drops off rapidly. Because of this, the part can "overshoot" the tolerance zone. Repeating this action is termed a *limit cycle*, where the system oscillates without convergence to the desired target. For this reason, actuation during fine part centering is done by pushing, where the position and energy input can be better controlled. Since actuation distances are so small, the previously described tangential force effect is relatively negligible, and the previously noted analytic treatments of static objects can be extended to the rotating part.

Transition from impact actuation to push actuation (or from coarse centering to fine centering) is not well-defined for this system. We have created an exponentially decaying function for defining actuation velocity. However, this is empirical only, and will be supported by the impact and stable pushing models in the near future.

3.4 Adaptation to Input Noise

Though modeling is employed to determine the actuation strategy, the simplified model is not completely accurate. Also, both physical noise, such as dust and lubricant, and electrical noise, such as EM interference, are present. All of these unknowns not modeled must be accounted for in the algorithm. To this end, a recursive compensation technique is employed.

The compensation offset has two components:

1) Gap Compensation $\mathbf{P_g}$. This occurs after an actuation when the part fails to move more than 3µm (just over centering tolerance). In this case, it is assumed that the actuator did not contact the part and the positional compensation of the difference between the known probe value at full closure and measured probe value is calculated.
2) Stroke Compensation $\mathbf{P_s}$. To obtain this value, the amplitude of the most recent actuation is found by

$$d_{actual} = \sqrt{r_{k-1}{}^2 + r_k{}^2 - 2r_{k-1}r_k \cos(\theta_k - \theta_{k-1})}$$

and subtracted from the previous desired movement vector (equivalent to the off-center distance).

The final positional compensation recursively added after modeling interval k is

$$P^{(k+1)} = P^{(k)} + P_g^{(k)} + P_s^{(k)}$$

The point of introduction of this technique, on the scale of off-center error, is important. If the mechanism is activated at too large an off-center value, overcompensation can occur, leading to limit cycle operation (i.e., part continually overshoots the target, error term does not converge). If the mechanism is activated at too small a value, the system may not be able to reach the compensation threshold due to noise contribution, and will settle into a pattern of stochastic movements outside of the target tolerance. We have found empirically for the ring mass range of 0.5kg-1.5kg, a threshold value between 0.2mm and 0.8mm is adequate to provide both compensation and convergence.

3.5 System Testing and Validation

The agile centering system has been tested in various cases across the applicable range as shown in Table 1.

Sample	OD [mm]	Mass [kg]	Contact Area [mm^2]	N_{pushes}	t_{cycle} [s]
1	123.9	0.77	113	5	31.2
2	170.0	1.20	77	8	45.8
3	88.9	0.88	141	4	25.5
4	98.0	1.25	39	5	29.4
5	77.6	0.45	66	5	28.4

Table 1-Results of Ring Centering (tolerance=2.5µm)

For the range of part mass 0.45kg-1.25kg centered to a tolerance of 2.5µm, the cycle time results are similar and comparable to the current manual centering capability. The cycle time result includes slide advance time and initial modeling time, but not slide retracting time. The centering process is repeatable and robust to different initial part placements up to 25mm off-center. No operator action is required other than initially placing the part and selecting the part type.

3.6 Context of Agility

The described system is designed directly as a component of the agile manufacturing system, defined as responsive to sudden and unexpected change. As the business system must be agile to market change, so must the manufacturing process be agile to part-by-part change. This system performs the centering operation of a part under manufacture irrespective of the size and condition and with minimal preprocess information. The data collected by the centering system can even be to generate and pass part information subsequently to the manufacturing process. Ideally, the system is able to operate in a piece-by-piece rather than lot-by-lot flow scheme with minimal required information and actually produces part identification information during its process, improving the agility of downstream operations.

The given system can be classed with "agile fixture design." Though in the presented case the part is not physically clamped, the locating function of agile fixturing is demonstrated. After centering, parts can be clamped by magnetic chucking without significantly affecting radial location. Also, parts of adequate mass and subject to minimal-force operations such as coordinate metrology will be sufficiently fixed by gravity.

4. Summary

The described system is capable of actively centering rotationally symmetric parts of up to 1.25kg to a tolerance of 2.5μm. This target has been achieved in our test cycles consistently in less than 1 minute, and is comparable to current manual centering techniques. Future specific work includes bettering the dynamic model of both impact and pushing, with the aim to capture the tangential friction effect to establish actuation rules and to define limitations.

Agility is defined as the ability of a system to adapt itself to rapid and unexpected changes. The proposed system can be used directly in the manufacturing process to allow processing of parts of various sizes and weights with little or no changeover time in between. Only software changes are required, and this input process can also be automated in the practical application. This minimization of type-to-type changeover time lets the centering system be agile with respect to manufacturing demand.

Currently, input of part geometry is required before cycling. As our testing broadens, this and newly-modeled information (*e.g.*, mass, contact area, moment of inertia) will be compiled into a lookup table with only discrete part selection provided by the operator or automatically selected by a Computer-Integrated Manufacturing controller. Future work can include addition of a vision system for part type recognition.

Not only is the centering system agile to part type input, but it can also respond to unexpected changes in its operating conditions. For example, if physical noise such as temperature fluctuation or mass flow of contaminants (*e.g.*, dust, lubrication) into or out of the system changes the expected sliding behavior of the part, the adaptation portion of the algorithm can modify the motion target and control parameters to adapt to the change in real time. Through this recursive adjustment technique, the system is agile toward part-to-part noise as well.

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