IMPLEMENTATION OF A TORQUE MOTOR INTO A
COMPUTER-NUMERICALLY CONTROLLED (CNC)
LATHE TOOL TURRET

Brian Heeran
Industrial and Systems Engineering

Matthew Buonanno
Mechanical Engineering

Owen Brown
Mechanical Engineering

Eric Newcomb
Mechanical Engineering

Steven Paul
Mechanical Engineering

Brice Wert
Mechanical Engineering

Robert Yarbrough
Mechanical Engineering

ABSTRACT
Hardinge Inc. is a world leader in production of high speed and precision computer-numerically controlled (CNC) machines. They are constantly evaluating newly emerging technologies for potential incorporation into future business opportunities. The Hardinge Universal Turret (HUT) design team has been given the task of redesigning a turret within a CNC lathe. With the main focus of the project centered around the implementation of a torque motor, Hardinge seeks to investigate all aspects of this marriage between performance and reliability.

INTRODUCTION
Hardinge Inc., founded more than 100 years ago, is a global leader in providing the latest industrial technology to companies requiring material-cutting solutions. The company designs and manufactures computer-numerically controlled metal-cutting lathes, machining centers, grinding machines and other industrial products. With its corporate headquarters in Elmira, New York, Hardinge is one of the area's largest employers, and has called the Southern Tier "home" since the 1930's. From this small-town location, they have etched out a worldwide reputation for excellence. Hardinge employs a highly trained and skilled global workforce, with over 1,000,000 square feet of manufacturing capacity worldwide. All employees make quality their number-one priority each and every day. Hardinge plans to build on the successes of the past 100+ years to forge an even brighter future.

The driving force for this project is derived from Hardinge's desire to maintain its industry-leading status. This project mainly falls into the realm of investigative research. Hardinge is constantly evaluating emerging technologies for possible inclusion into future designs. The scope of this project is limited to computer-numeric controlled lathes. The design team has been given the task to develop a turret index model that incorporates the use of a torque motor. This motor will intern serve the function of indexing the top plate, and does not focus on the main spindle drive motor or the driving of any live tooling applications. The characteristics of a torque motor allow for increased reliability by removing the need for a gearbox. This also allows for the potential passage of a live tooling drive shaft directly through the centerline of the top plate. One main design objective is to prove the feasibility of using a torque motor and the resulting influence on the current design, e.g. the removal of the gear box utilized by the current top plate drive motor.

NOMENCLATURE
\[ I_c = \text{constant input current (A)} \]
\[ J = \text{moment of inertia (kg-m^2)} \]
\[ K_T = \text{torque constant (N-m/A)} \]
\[ K_U = \text{back EMF constant (V-s/rad)} \]
\[ L = \text{inductance (H)} \]
**DESIGN OBJECTIVE**

The design objective for the HUT team has evolved many times over the course of the project. Originally, the primary objective was to design a turret that was powered by a torque motor specified by the design team. This turret was to allow for the addition of live tooling, the use of a uniform tooling standard, and the reuse of as many components as possible from Hardinge’s inventory. However, as dictated by the project sponsor, those objectives were streamlined and reduced to designing a prototype that is powered by a torque motor. From these design objectives, the HUT team derived performance specifications for determining a successful prototype.

It became clear that the project sponsor’s main concerns, regarding the performance of the turret design, revolved around overall indexing time and whether the new thermal properties of the turret required the application of liquid cooling.

A successful turret resulting from this project is one that incorporates the following:

- Use of a torque motor
- Use of Hardinge locking coupler
- No liquid or forced-air cooling
- Indexing time of approximately 0.1 seconds
- Use of standard top plate with 12 tooling stations

**BENCHMARKING**

In order to effectively evaluate a turret design powered by a torque motor, the HUT team conducted an extensive benchmarking study focusing on a wide array of current turret offerings. This study includes both Hardinge and four other industry leaders: Diplomatic, Loshin, Pragati, and Sauter. Data obtained from the benchmarking study was used in determining the technical and performance criteria of torque motor designs. Once the criterion was established the team set out to develop a design, which exceeded these expectations.

**Turret Selection**

Turrets were chosen from each manufacturer that represented a sampling of performance capabilities. As a general guideline, models were chosen that were similar in size to a 12-station turret in order to maintain data compatibility across the evaluation criterion.

**Evaluation Criteria**

Due to the complexity of a CNC turret, the HUT team decided to break down a multitude of characteristics into separate categories for evaluation. After consulting with the team sponsor, the characteristics that were determined to be most important were designated as "Primary", slightly less important characteristics were listed as "Secondary".

Primary Characteristics are as follows:

- Index Time, Index Motor, Number of tooling stations, Turret Operation, Max Torque, and Total Turret Weight.

Secondary Characteristics are as follows:

- DIN Standard Size, Turret Operating Pressure, Number of Turret Control Valves, Turret Centerline Height, Max. Allowable Coolant Pressure, Mounting Diameter, Live Tooling Speed Max, Turret Weight w/ Y Axis, Max Tool Load, Backworking Design, Y-Axis Available, Tooling System Standard, Non Live Tooling Turret Option, Top Plate Across Flats, Live Tooling Motor, Coolant Feed Capabilities, Repeatability, Live Tooling Horse power Max, Spindle Precision, Tool Mounting, Tool Interface, Tool Drive Spline Size

**CONCEPT DEVELOPMENT**

During the brainstorming phase of concept creation each mechanical engineer of the HUT team was asked to conceptually develop a design. Team members were given the parameters to work individually and to integrate a torque motor. Team members were then asked to prepare a short presentation including computer-aided drafts, of their conceptual design. As the team began to examine different conceptual designs, it became apparent that each had something to offer in the development of the preliminary design.

**FEASIBILITY ASSESSMENT**

One of the most widely used methods of design concept selection is that proposed by Pugh. Pugh's method rates a set of proposed design concepts with respect to a selected datum concept. In utilizing this method for the design, the lists of technological and
performance requirements were ranked in order of importance. The higher ranked attributes were assigned more points then the lower. This was done in order to weight the total scores accordingly. The Hardinge Talent 10/78 series turret was used as the datum. The total scores for each design were then compared, with the highest point total indicating the preferred design. Pugh’s method for both technological and performance requirements are listed below as table 1 and table 2.

### Technological Assessment

<table>
<thead>
<tr>
<th>Requirements</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Motor</td>
<td>52</td>
<td>64</td>
<td>48</td>
<td>62</td>
<td>58</td>
<td>62</td>
</tr>
<tr>
<td>Freest Parts</td>
<td>-30</td>
<td>9</td>
<td>-24</td>
<td>-3</td>
<td>-6</td>
<td>3</td>
</tr>
<tr>
<td>Locking Mechanism</td>
<td>-8</td>
<td>24</td>
<td>5</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>On-Shelf Use</td>
<td>-4</td>
<td>56</td>
<td>32</td>
<td>24</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Hollow Cavity</td>
<td>-2</td>
<td>16</td>
<td>-4</td>
<td>-2</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Tooling Load</td>
<td>-8</td>
<td>-5</td>
<td>-3</td>
<td>-6</td>
<td>-5</td>
<td>-6</td>
</tr>
<tr>
<td>Housing</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Control Compatibility</td>
<td>-3</td>
<td>-2</td>
<td>-3</td>
<td>-2</td>
<td>-3</td>
<td>-2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>18</td>
<td>184</td>
<td>92</td>
<td>101</td>
<td>126</td>
<td>137</td>
</tr>
</tbody>
</table>

Table 1: Pugh’s Method: Technological Requirements

### Performance Assessment

<table>
<thead>
<tr>
<th>Requirements</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability</td>
<td>16</td>
<td>30</td>
<td>18</td>
<td>30</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td>Index time</td>
<td>15</td>
<td>21</td>
<td>15</td>
<td>18</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Reliability</td>
<td>5</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Stiffness</td>
<td>2</td>
<td>22</td>
<td>18</td>
<td>14</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Cooling</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mass Properties</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>39</td>
<td>97</td>
<td>61</td>
<td>74</td>
<td>66</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 2: Pugh’s Method: Performance Requirements

### Economic Assessment

The uniqueness of this project limited the possibility of performing feasibility assessments on the economic and scheduling aspects. The sponsor provided the design team with all necessary components. Purchasing was handled directly through the sponsor due to the long lead times and high costs associated with computer numerically controlled components. The design team was directed to focus on long term cost estimates revolving around the torque motor, machined components, and the associated assembly time. The requirements for both economic and scheduling aspects are listed below:

- Conceptual Design
- Detailed Design
- Analysis
- Prototyping
- Manufacture & Assembly
- Testing
- Documentation

Part of the economic conceptual design was utilizing the reuse of as many existing Hardinge turret components as possible. This provides an economic benefit to the project sponsor, who prior to this, has redesigned and manufactured required components on a model-by-model basis. The fact that the project sponsor will utilize previously developed components reduces the overall lead-time associated with the assembly. Incorporating off the shelf components lends itself to a proven track record of reliability, requiring no additional engineering analysis. Given the inherent difficulty in ranking the HUT team’s conceptual designs, schedule and economic concerns were used as metrics while in the early portion of the project. As the project scope narrowed to developing a simple turret-indexing model while incorporating the use of a torque motor, the associated scheduling concerns were removed.

At the conclusion of implementing Pugh’s method, design number 2 was the clear winner in both performance and technological requirements. Because the disparity between design 2 and the next highest score, it was concluded that another iteration of Pugh’s method was not necessary.

### DESIGN SPECIFICATIONS

The design of the turret is based around three main factors, speed of response, stiffness, and heat removal. The speed of the response is directly coupled with the torque motor; the dynamics and response of this motor will be discussed under the engineering analysis section of this paper. Since the torque motor is a requirement of the design, there is no question about its involvement. Most of the stiffness problems have been solved previously and the use of an existing turret coupler reduced the amount of redesign significantly. In order to accommodate this part and still maintain stiffness in the design, it is necessary to maintain large wall thicknesses on the housing that holds the coupler. This minimizes the deflection due to the new components. Further, the idea has been implemented throughout the design producing a fixture with extremely high stiffness, and durability. These characteristics are also seen in the bearings, which based on calculations, have infinite life in the turret.

The bearings are also situated to reduce any loads on the motor and fully support the top plate when it is carrying a high tool load. Considerations were also given to crash loading of the turret while uncoupled and indexing; the bearings chosen were designed to handle this most efficiently.

### TORQUE MOTOR

Torque motors were benchmarked based on common sizes of models from various companies, including Etel, Siemens, and Bosch Rexroth. They were compared based on nine key features eight of which were technical and the ninth and dominating factor was cost. The technical motor comparison focused on the physical size, torque, power, and mass properties with each of these composed of main areas of consideration.
**Physical Size**
The stator’s outer diameter is very important since the motor absolutely cannot exceed the diameter of the standard top plate. Exceeding this would mean that the top plate would crash into the work piece, however this also drives the amount of torque that can be provided by the motor, the larger the diameter, the larger the moment arm provided by the motor. The team came to the obvious conclusion that in order to maintain proper clearance with any additional parts needed to mount the stator, a motor approximately 100mm smaller than the outer diameter of the top plate should be selected.

Motor length also drives the amount of torque that can be provided by the motor to the assembly, the longer the motor, the longer the magnets, the larger the magnetic potential, the higher the torque that can be provided by the motor. Once again there is a size constraint in the design; the motor length cannot be so long that it interferes with any of the shafting that needs to go into the outer housing of the turret, which cannot increase in size as the result of our design. It was decided to use the shortest possible motor that would also meet the project torque requirement.

**Torque**
The torque of the motor drives the system response to electrical input, thus in order to both predict the station-to-station index time, the torque that the motor can provide must be known. The continuous torque is the value of torque that the motor can sustain for an indefinite portion of time. The peak torque is the torque that the motor can run at for a certain specified period of time.

**Power**
Power is one of the best overall characteristics of a motor, as it tells a significant amount about what the motor is capable of. The input power is the power required by the motor in order to run at its optimal conditions. In some cases this power was given as a motor parameter, in other cases it had to be derived from the equation for electrical power:

\[ P_{in} = \frac{3}{2} \cdot \left[ R_C \right] \cdot I_C^2 \]  

The output power is defined by the amount of power available at the motor shaft. In some cases this was given and in others it needed to be calculated by using the equation for output torque given by Eq. (2).

\[ P_{Out} = \omega_{Const.} \times T_{Const.} \]  

**Mass Properties**
The mass properties of the motor are critical to understanding how much the turret will weigh, and thus how much force it will take to move the turret around in the lathe. Also critical to the design process is that the mass moment of inertia of the rotor is known. This is required in the model of how the turret will respond to electrical input for indexing. This will be explained in further detail later in this document. Both of these properties of the motor are supplied by the manufacturers of the torque motors.

**Other Non-Technical Factors**
Unknown to the team during the initial benchmarking of the motors, our sponsor previously had spoken with and decided on a motor supplier due to various other factors. Not least of these factors is price. Also, there had been some discussion of using a custom motor in the final production assembly in the event that there would ever be such a product taken past the prototype stage. Also, configuration of the motor wiring was a considerable factor in their decision, this is something the team could have had no idea of during the initial benchmarking. Etel Inc, the supplier that the sponsor chose, offered to provide a low cost torque motor solution for the project provided that it came from their current inventory in Switzerland. Etel gave the following torque motor sizes to choose from:

- TMA0210-030
- TMA0210-050
- TMA0210-070
- TMA0210-150

These motors have various stator options with different sensor and inputs standard on the stator.

**Dynamic Response to Electrical Input**
There was a general idea of what could be expected for the torque motor, the team had all of the technical data sheets for these motors so work began on a model of the system dynamics using each of these motors in order to predict the behavior of the assembly. The first thing that was done was to use the CAD drawings of the top plate assembly to determine a rough estimate of the inertia that the motor would have to move through each indexing position. The team utilized the following equations to arrive at the dynamic response to electrical input:

\[ \sum T = J \ddot{\theta} \]  

Assuming rigid body motion the torques can be summed up as shown here:

\[ \sum T = T_m - T_F \]  

So the equation for the motor torque is given here as:
\[ T_m = K_T \frac{e_S - K_U \sigma}{L \cdot S + R} \quad (5) \]

Back substituting Eq. (5) into Eq. (4) yields:

\[ \sum T = K_T \frac{e_S - K_U \sigma}{L \cdot S + R} - T_F \quad (6) \]

This equation in turn can be substituted into Eq. (3) and solved for the angular acceleration:

\[ \ddot{\omega} = \frac{1}{J} \left[ K_T \left( \frac{e_S - K_U \sigma}{L \cdot S + R} - T_F \right) \right] \quad (7) \]

Using the definition of angular velocity we can complete the systems model:

\[ \dot{\theta} = \omega \quad (8) \]

The open loop model of the system was placed into Simulink to approximate the system response for the various motors. The response of the various motors to this input were compared, however it was quite clear that all of the motors of this size range will produce adequate torque for the application of indexing the turret.

**Final Motor Selection**

Based on the dynamic response data, the team selected the high-end model of these motors, the TMA0210-150. The dynamics response for the TMA0210-150 motor can be seen in Fig. 1. The team decided that this motor would give ample options for torque, while still leaving a large enough inner diameter to pass shafting for any sort of live tooling that might be added at a later point to the prototype by the sponsor.

**Heat Dissipation From the Motor**

Since the motor has no available liquid cooling option at the sponsor’s request, the heat dissipation of the motor is quite critical for our application. There was a need to run some basic heat calculations based on the motor selection to see what kind of accessory cooling options were needed, or if reducing the coil temperature in the controls was a possibility. The motor manufacturer supplied the three equations shown below to aid in these heat calculations.

The first of the three equations corrects the coil resistance for temperature change.

\[ R_C = R_{20} \left( 1 + 0.0039 \times (\theta_C - 20) \right) \quad (9) \]

The second gives the equation for the power dissipated due to the copper losses in the motor. Note that the built in factor of safety in this equation is 1.5, this was recommended by the manufacturer, and as such, was not removed in our calculation.

\[ P_C = \frac{3}{2} R_C \cdot I_C^2 \quad (10) \]

The last equation relates the coil temperature to the ambient temperature and the power lost in the coils.

\[ \theta_C = \theta_{amb} + P_C \cdot R_{th} \quad (11) \]

From these equations, varied results that were previously unpredicted occurred. The first is that a peak torque in the motor occurs as it is just turned on since the coils are cool and have a low resistance. The coils draw more current when cool, than they would if they were warmer. This peak torque then trails off, as expected because of the reduced current. The model however fails to account for the electro-magnetic saturation of the motors and the 0 current points, which causes a spike and is unrealistic of the actual operational performance. This is seen in Fig. 2.
Heat removal is one of the most crucial elements of the design, to ensure an adequate steady-state operating temperature; different cooling options were sought out since the heat generated in the motor is high enough to burn out the coils in the stator. While in a closed house design, the team will implement these changes, as heat removal becomes a persistent issue around the torque motor:

- Ventilation slits will be added to the top of the housing to allow for heated air to escape by means of natural convection.
- Small AC powered fans will be added to the sides of the housing to force air out of the top of the structure.
- Custom heat pipes, made of copper pipe and filled with distilled water will be made to “hug” the contours of the torque motor and draw heat away by taking advantage of the liquids phase change.

The cooling specification was based off of research for electrical heating. The torque motor, at worst case scenario, will produce close to 1000 watts of power. This power will be transferred to about 0.15 m$^2$ of exposed surface area around the stator of the motor. In industry, the team uncovered that a good rule of thumb was to use the following calculation for cubic feet per minute of air to hold a desired temperature:

$$CFM = \frac{3.16 \cdot W}{\Delta T_{Allowed}}$$  \hspace{1cm} (12)

Using that rule of thumb, we allowed for a maximum ambient temperature of 70°F, and a maximum allowed temperature of 200°F. Using the power output of 1000 W we have the following:

$$CFM = \frac{3.16 \cdot 1000W}{200° - 70°} = 24.3$$  \hspace{1cm} (13)

Based on that calculation, a small fan capable of moving approximately 30 CFM should be more than suitable for preventing the torque motor from overheating. In summary, based off of a 20% duty cycle, both our data and Etel’s concur that the motor should not over heat the 115° C (239°F) critical mark inducing coil meltdown. However, after meeting with a representative from Etel motors and based on the above predicted duty cycle, the design team was assured that free air convention would more than adequately handle the cooling of the torque motor.

**PROTOTYPE FABRICATION**

During the fabrication of this prototype turret the team encountered several difficulties. The HUT team was forced to use a specific supply company for which the stock 1018 CD steel was to be purchased. The abilities of the supplier to deliver standard sized steel were limited due to supply and the order lead time limitations required by the team. Therefore, the HUT team was forced to purchase much larger stock size material for each component. This added numerous hours to the production of each component. The HUT team split the fabrication process between the Brinkman and Mechanical Engineering labs. Although the HUT team was able to minimize the amount of parts needed to be produced through the reuse of as many parts as possible, machining several parts, there was one remaining component we were unable to produce. The HUT team originally proposed that the project sponsor produce this component, however at their request the team sought to outsource the shaft to a local machine shop. After a long and thorough search Hardinge agreed to produce this component in house. However, it is important to note that several weeks of fabrication time were wasted attempting to outsource the shaft.

**ACKNOWLEDGMENTS**

The HUT team would like to thank the following people for their help with this project. First, the team would like to thank the project sponsor Hardinge, Inc., who has been extremely helpful in answering the team’s questions and getting the supplies and tools needed in order to complete a successful project. The team would particularly like to thank the New Product Development Manager, James Peris, as well as Senior Engineer, Mark Tuccio. Without them this project would not have been possible.

Also, thanks to ETEL, Inc. and Vice President and General Manager Arthur Holzknecht who has worked with the team in selecting a torque motor to use for this application. The team also gives special thanks to faculty mentor Dr. James Taylor for his constant vigilance and guidance throughout the project, and faculty coordinator Dr. Jacqueline Mozrall for her assistance with course deliverables. Finally, the team would like to thank the following college of engineering staff for their assistance and guidance during the prototype fabrication phase of the project: Mr. John Bonzo – Industrial & Systems Engineering Facility Director, Mr. Dave Hathaway - Mechanical Engineering Facility Director, Mr. Steve Kosciol Senior Mechanical Technician and Mr. Rob Kraynik Senior Mechanical Technician.

**REFERENCES**