Development of Multi-Degrees of Freedom Optical Table Dynamometer

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Abstract
Accurate measurements of cutting forces are critical in machining operations for maximizing production, detecting tool wear and failure, adaptive control and monitoring. Traditionally, cutting forces are measured using piezoelectric quartz force sensors or strain gauges. These types of sensors have limitations in that they are unable to measure static force signals. The quartz crystals of a piezoelectric force sensor generate an electric charge only when force is applied to or removed from them. Strain gauges suffer drifts over a long period time. In order to overcome the challenges, a novel table dynamometer is developed based upon laser optics to measure planar forces and moments in both the static and dynamic range. The developed table dynamometer allows the measurement of both the in plane linear movements and the in-plane rotations. In order to achieve high sensitivity, a monolithic, flexure-based mechanical amplifier is adopted into the proposed table dynamometer. A prototype of the developed system is fabricated and the sensitivity and frequency bandwidth of the system are experimentally investigated. The results showed good agreement between the optical force sensor and a reference force transducer. The proposed dynamometer is tested for use in the measurement of cutting forces and compared with a conventional piezoelectric dynamometer.

Keywords: Force Sensor, Dynamometer, Laser, Optics, Mechanical Amplifier

1 Introduction
The measurement of forces is essential in many areas of science and engineering. In the field of manufacturing industry, measurement of forces during material removal operations can result in the indirect measurement of other important machining process parameters. It can be utilized to understand the machinability of the workpiece material by correlating the amount of removed material and measured forces. Understanding the amount of forces involved in the machining processes combined with the dynamic characteristics of the machine tool has led to the prediction of finished surface quality (Thiele, et al., 1999) and chatter stability (Budak, et al., 1998). In addition, force measurements may also be the indicator of the tool wear as the thrust component of the cutting force increases as the flank wear of the tool becomes excessive (Kline, et al., 1982). Also the tool breakage
could be identified by monitoring force measurements as the cutting force magnitudes abruptly change when one of the milling cutter teeth chips or breaks (Altintas, 1994). With a wide range of phenomena that may be detected through force measurement, the use of reliable force sensing methods to monitor machine tools has the potential to increase the useful machining time of a given machine tool from 10 to 65 percent (Tonshoff, et al., 1988). Furthermore, the adaptive control of machining processes, which is most effective when cutting force data is used as the feedback parameter, can significantly boost overall productivity, prevent excessive deflection of tools and prolong the longevity of tools. The recent emergence of the concept of Smart Factory, or the 4th generation manufacturing industry (Industrie 4.0), has raised the importance of monitoring the forces even further (Lucke, et al., 2008). In this concept, individual modules of the system monitor the manufacturing process and communicate the measured data between each part of the machine as well as the operator in real time, and optimize the process automatically based upon the measured data and the simulation algorithm. Measurement of forces is the fundamental source of information to create the cyber-physical systems in the machining processes.

The accurate measurement of forces, however, has been a challenging task due to a number of reasons. With regards to micromachining specifically, the frequency bandwidth of commercially available force sensors is inadequate for the majority of micro-machining cutting-force frequency regimes due to the very high rotational speeds used for micro-milling processes. Also any force sensing system that is remote to the cutting tool has a limited frequency bandwidth caused by dynamics of the mechanical elements located between the cutting point and sensors (Albrecht, et al., 2005). In terms of conventional piezoelectric force sensors, a significant limitation is their inability to measure static forces. The quartz crystals of a piezoelectric force sensor generate an electrostatic charge only when force is applied to or removed from them. Even though the insulating electrical resistance of the sensor, cables and amplifier is quite large, the electrostatic charge will eventually leak to zero through the lowest resistance path, causing the signal drift. The inability to accurately measure the static component of forces often results in force measurements matching the expected forces in qualitative analysis of the machining processes, but not in the quantitative terms.

Force sensors for static and slower dynamic force measurements are based on strain gauges. They are used because of their ease of application, and comparatively low cost to piezo transducers. The most widely used characteristic that varies in proportion to strain is electrical resistance. Although capacitance and inductance-based strain gauges have been constructed, these devices' sensitivity to vibration, their mounting requirements, and circuit complexity have limited their application. Unfortunately even resistive strain gauges have limitations. They suffer from stability problems. In calibrated strain gauges, the passage of time always causes some drift and loss of calibration. Hysteresis and creeping caused by imperfect bonding is one of the fundamental causes of instability (Omega 1995). Strain gauges are also sensitive to temperature, vibration, acceleration and shock; they require proper protection as exposing a strain gauge transducer to conditions outside its operating limits can degrade performance. These limitations are all in addition to the frequency limitations as mentioned previously.

The overarching goal of this study is to develop a cost-effective platform to accurately measure forces in multiple degrees-of-freedom (MDOF), with high sensitivity and sufficient frequency bandwidth to be applicable in micro machining processes with small forces and high spindle speeds. A novel laser-optics based dynamometer design is proposed. In order to achieve the MDOF measurements capability, an optical model is developed to decouple translational and rotational effects from the measured signals. Also a flexure-based mechanical amplifier is adopted to increase the sensitivity and the precision of measurements.

In the following section of this manuscript, the overall design of the proposed system and how the measurement is made in the system is described. The development of the optical model and the mechanical amplifier is described in detail, followed by the experimental processes and their results to evaluate the developed system. It is summarized with a discussion of possible future studies.
2 Design and Fabrication

In the proposed optical table dynamometer system, it contains mechanical, optical and electronic components. The fundamental concept of how the system measures forces is described in this section. First, the force is applied to the top surface of the sensor (the actuator pad), and the resulting forces are transferred to the stiffening plate and produce a minute deformation. The stiffening plate is responsible for setting initial sensitivity of the system. A more flexible plate allows higher deformations to be realized, improving sensitivity while decreasing range, and a thicker, more rigid plate would allow larger force measurement ranges at the cost of resolution. This is due to the fact the stiffening plate is coupled to the input side of the MDOF mechanical amplifier which magnifies the input deformation at the output. The laser target surface is fixed to the output stage of the amplifier where its position and orientation are changed due to the output deformation. The altered position of the laser target surface is then tracked by cost-effective laser diode modules with two laser sources (635 nm collimated laser diodes) and a four-quadrant photodiode detector. The electrical signal generated from the detector is then fed into the uncoupling ray tracing algorithm where the change in position of the target surface is reconstructed to extract X and Y linear motions as well as rotations about Z axis. The schematic of the produced prototype is shown in Figure 1.

For MDOF measurements, multiple laser sources and multiple photodetectors are required to fully define the motion. In this study, a single photodetector is used with two pulsed laser sources where each laser interfaces with the target surface. In addition, an oscillating detector is utilized to allow a fully defined MDOF motion (including rotational moment) to be reconstructed.

3 Methodology

In this section, the ray tracing technique and the design of mechanical amplifier are introduced. The ray tracing algorithm follows the optical model to decouple linear translational displacement measurement from the rotational angular displacement. The design of mechanical amplifier is also described with the simulation results and the resulting amplification ratio in each axis of motion.
3.1 Decoupling of Laser Signals

The measurement technique of ray tracing is based on position measurements of two collimated light sources that are reflected off of the target of interest. These reflected light beams are then measured with a four-quadrant (two-dimensional) position sensitive photodiode (PSPD). Based on the known geometric relations between the laser source, reflecting target and photodiode, the translational and angular displacements of the target can be determined. The ray tracing analysis allows the tracking of a target surface to directly determine its position and orientation. A general scenario for ray tracing is shown Figure 3.

A difficulty in the ray tracing analysis arises when MDOF measurements are required. In vibrometer (Trethewey, et al., 1993) and optical position sensor (Bokelberg, et al., 1994) designs similar to the proposed optical force dynamometer, multiple pairs of laser and detectors are utilized to take MDOF measurements. In order to reduce cost and complexity, a new approach is taken whereby multiple laser diodes are used along with a single photo detector, where laser diodes are pulsed in alternating manner. This method permits the explicit determination of the in-plane position (x and y positions) of the target surface.

![Figure 2: General laser path tracking schematic](image)

In order to determine the in-plane angle (i.e. moment) of the target surface, additional information is required because the translational and rotational variables of a target surface cannot be uniquely defined using only a two source-single detector set. To address this limitation, a novel vertically oscillating photodetector method is introduced. In this method the photodetector element is vibrating in a synchronous manner relative to the pulse frequency of the laser sources. This vibration of known amplitude leads to a corresponding shift in the detector measurements, allowing both the incident light position and its trajectory to be identified. This additional information fully defines the translational and rotational deflections of the target surface in the x-y plane. The identification of these parameters is essential in the calculation of forces and moment. With a known deflection and stiffness (from the mechanical amplifier) the resulting forces can be measured. A schematic of the system is shown in Figure 3.
Based on Figure 3, the global reference frame of the force sensor is fixed and defined as Frame 0. It is located at the target surface attachment point from the mechanical amplifier. The next important frame to define is the local reference frame of the target surface. This frame (Frame 1) is initially coincident to the global frame and the relationship between this frame and the global frame explicitly provides the desired pose variables. The transformation matrix of Frame 1 relative to Frame 0 is defined as:

\[
0T = \begin{bmatrix}
\cos \theta_1 & -\sin \theta_1 & X_1 \\
\sin \theta_1 & \cos \theta_1 & Y_1 \\
0 & 0 & 1
\end{bmatrix}
\]  

where \(X_1\) and \(Y_1\) are the desired pose variables and \(\theta_1\) is the static tilt of the target surface. With the initial positions of all components defined in global space, the next step becomes to track the laser beam along its optical path, first reflecting off of the target surface and reaching the detector.

With all the pertinent geometry defined, there is a triangle formed with its vertices at the three points, \(\Delta P_{L1}P_{R1}P_{D1}\) (see Figure 4).

Using simple trigonometric relations not shown here, the triangle can be fully defined and the location of the first reflected point is known relative to frame 0, the same calculation procedure for \(\overrightarrow{0P_{L2}P_{D2}}\), \(\beta_2\), \(\alpha_2\), \(\overrightarrow{P_{L2}P_{R2}}\), and \(\overrightarrow{0P_{R2}}\) is repeated for the opposite side of the system. As a result, the known positions of \(\overrightarrow{0P_{R1}}\) and \(\overrightarrow{0P_{R2}}\) can now be used to determine the location of the target surface. The
The fact that these two points must lie on two lines orthogonal to one another is the proof. Calculate the vector from \(0P_{R1}\) to \(0P_{R2}\) as shown in the following equations (see Figure 5):

\[
\frac{0P_{R1}0P_{R2}}{0P_{R1}0P_{R2}} = \frac{0P_{R1}0P_{R2}}{0P_{R1}0P_{R2}} \cdot \cos \delta \\
= \frac{(P_{R2x} - P_{R1x})^2 + (P_{R2y} - P_{R1y})^2}{\sin \delta}
\]

\[
\delta = \arctan \left( \frac{P_{R2y} - P_{R1y}}{P_{R2x} - P_{R1x}} \right)
\]

With the vector \(0P_{R1}0P_{R2}\) fully defined the distance and angle from one reflected point and to the target surface may be determined. This step makes use of the fact that the vector calculated in the previous step forms a right triangle with the intersection of the target surfaces. The adjacent angle to the triangle, \(\tau\), can be determined from Figure 12. The length of the adjacent side is the hypotenuse multiplied by the cosine of the angle \(\tau\).

\[
\tau = \delta = \theta_1 + \frac{\pi}{4}
\]

\[
0P_{R1}0P_{TS} = 0P_{R1}0P_{R2} \cos \tau
\]

The angle of this line in global coordinates can also be determined as \(7\pi/4 + \theta_1\). With the length and angle of the line connecting \(0P_{R1}\) to \(0P_{TS}\) the global coordinates of the target surface vertex are calculated as:

\[
0P_{TS} = 0P_{R1} + \frac{0P_{R1}0P_{TS}}{0P_{R1}0P_{TS}} \left[ \frac{\cos \left( \frac{7}{4} \pi + \theta_1 \right)}{\sin \left( \frac{7}{4} \pi + \theta_1 \right)} \right]
\]

![Figure 5: Calculation of \(0P_{R1}0P_{R2}\)](image)

![Figure 6: Locating the target surface in global coordinates](image)
Now the vertex of the target surface has been described in two frames (Frame 0 and Frame 1). These two points can be equated through the homogeneous transformation matrix to determine the desired pose variables of the system.

\[
0^p_{TS} = 0^T_{1} P_{TS} = \begin{bmatrix} P_{TSX} \\ P_{TSY} \\ 1 \end{bmatrix} = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & X_1 \\ \sin \theta_1 & \cos \theta_1 & Y_1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ y_{TS} \\ 1 \end{bmatrix} \quad (21)
\]

Row one and two can now be used to solve for the unknown pose variables.

\[
X_1 = P_{TSX} + \sin \theta_1 y_{TS} \\
Y_1 = P_{TSY} - \cos \theta_1 y_{TS} \quad (22)
\]

The solution algorithm presented in this section allows for the identification of the deflections of a target element relative to its base frame. In order for the laser diode pulses to line up with the minimum and maximum amplitudes of the oscillating element thereby maximizing resolution and minimizing error, their signals must be synchronized. Figure 7 depicts the necessary signal synchronization scheme to have a functioning laser pulsing, photodetector oscillating circuit.

![Figure 7: Laser and piezo-actuator synchronization scheme](image)

It is observed that the duty cycle of the laser sources has to be kept less than 50% to ensure the switching time delay does not interfere with the other signals. The interference between signals could cause crosstalk in measurements between two signals. Accurate control of this parameter is paramount for effective switching and signalling at higher frequencies.

### 3.2 Mechanical Flexure based Amplification

To increase the sensitivity and the precision of measurements taken from the photodetector, a monolithic flexure-based mechanical amplifier is adopted. Flexure system consists of a combination of rigid and flexural elements. These elements are arranged and interconnected in a way that they allow
specified motions along compliant pathways while restricting motion in all other directions. Flexure systems have been used as precision machine elements for over a century due to their excellent resolution, low-cost, and the ease of manufacturing (Hobkins & Culpepper, 2011). Flexure systems continue to be important to conventional precision applications, for instance they are commonly used within optical manipulation stages, precision motion stages and as general purpose flexure bearings.

In the flexure system considered here the principle elements are third class levers. The input marked by the red box acts as the force application point onto the first lever. This movement is then amplified by the ratio of distances between the fulcrum and displacement point and the fulcrum and the force application point. As the input is transmitted through the amplification stages, the point of displacement of the current lever acts as the force application point of the next stage. This configuration enables a cascading effect in magnification. The entire system contains three lever stages and the output of the system is depicted by the green box. The overall amplification of the system is the product of the amplification factor of each lever step. The schematic illustration of cascading serial flexure amplifier is shown in Figure 8.

![Cascading Serial Flexure Amplifier](image)

**Figure 8:** Cascading Serial Flexure Amplifier

In the case of the optical force dynamometer, the mechanical amplifier is the stage that converts the force applied at the sensor input, to the change in position of the target surface. This change in position causes the laser beam generated by the laser diode to alter its trajectory and strike the photodetector at a new location, indicating the application of a force. The simulation results are shown in the following two figures. Figure 15 shows the simulation results with the external force applied along the y-direction. In this case only the main diagonal amplifier legs transmit the force through to the output stage while the off-diagonal legs do not contribute. Analysis of the crosstalk is also shown in Figure 9. The off-axis displacement is an order of magnitude less than in the applied force direction at the output stage. This indicates that the two amplifier degrees-of-freedom are sufficiently isolated from one another. The results from the simulations are tabulated in Table 1.
Figure 9: In-line and off-axis force application on a 3-DOF flexure amplifier

<table>
<thead>
<tr>
<th>$K_x$ (N/μm)</th>
<th>$K_{xy}$ (N/μm)</th>
<th>$K_y$ (N/μm)</th>
<th>$K_{yx}$ (N/μm)</th>
<th>$K_{θz}$ (Nm/°)</th>
<th>Linear Amplification Ratio (μm/μm)</th>
<th>Angular Amplification Ratio (μrad/μrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.905</td>
<td>5.72</td>
<td>0.919</td>
<td>5.84</td>
<td>46.24</td>
<td>2.82</td>
<td>7.28</td>
</tr>
</tbody>
</table>

Table 1: Mechanical amplifier characteristics

The amplifier is shown to have an amplification ratio from input to output of 3.14 and a resultant stiffness of 0.85 N/μm. The off-axis effects are minimized due to the increased stiffness of 9.94 N/μm (over an order of magnitude). Due to the symmetry, the results in the other degree of freedom are nearly identical.

4 Results and Discussions

The developed system is calibrated and tested for both the static and the dynamic force measurements. The ray tracing and uncoupling models are applied to extract force measurements from the measured photodetector data. The results of this sensing platform under both static and dynamic loading scenarios are examined.

4.1 Sensitivity and Frequency Bandwidth
For the static stair step force test setup, a digital force gauge (Omega DFG51-2) was utilized to apply the forces and set the reference force measurements. The PSPD data signals are collected through BNC cables and connected to a digital oscilloscope with data logging functionality. The forces measured in the developed optical force dynamometer were compared to the reference forces in both the X and Y axis (see Figure 16). Similar experiments were performed to measure the applied torque $M_z$, where a lever with known length is fixed to the actuator pad and a known force is applied.

Prior to the testing, the system is first calibrated using the force gauge. Known forces are applied to the sensor and the corresponding voltages are recorded. Using linear regression, the sensor is found to have a sensitivity factor of 1.25 N/mV and 1.21 N/mV in the X and Y directions, respectively. The crosstalk effects are neglected for the purposes of this analysis. Once the calibration coefficients have been identified, the system is given a staircase reference function along a single measurement axis. The resulting calibrated curve in the x and y directions and about the z-axis are given in Figures 17, 18 and 19, where OFS stands for the optical force dynamometer measurements and OMEGA stands for the measurements from the reference force gauge. The data is filtered through a moving-average filter with a window of 4.

The results show good response and tracking to the reference signal. In this experimental setup, there are a number of sources of error. The reference force signal was generated through manual application of force and only the ideal representation is shown in the figured. This is most likely the primary factor causing the deviation in both the time scales as well as the overshoot observed at each step in the graph. It’s very likely that the overshoot visible in the curve produced by the proposed dynamometer would also be shown in the reference sensor had we been able to data log its response in real time as well. In future testing a better controlled reference force scheme is required to aid in assessing the sources of error.
Figure 11: $F_x$ force comparison

Figure 12: $F_y$ force comparison

Figure 13: $M_z$ static torque comparison
Dynamic evaluation of the system is limited to measurement of the usable frequency bandwidth. Impact hammer testing is performed with an instrumented hammer (PCB 086E80) and data is collected through a data acquisition board. The results of the hammer testing are shown in Figure 14.

The proposed optical dynamometer is compared to the commercially available table dynamometer (Kistler 9256C2). Both were tested while clamped to a vibration isolation table to create similar boundary condition. The piezoelectric dynamometer shows a dynamic range of approximately 2 kHz. The proposed optical table dynamometer shows similar results and behaves like the commercial sensor up until near 100 Hz. At this point the sensor begins to deviate quite severely. It is postulated that the principle cause of these unwanted dynamic effects is due to the mechanical system and enclosure of the sensor. As the primary structure is composed of acrylic plastic the system lacks the inherent stiffness quality of the corresponding piezoelectric dynamometer made principally of steel alloy with high clamping preloads on all sensing elements. Improving the dynamic performance of the optical dynamometer is discussed further in the next section.

4.2 Cutting Tests

In order to assess the dynamic performance of proposed dynamometer, milling cutting tests were performed. In this case the workpiece was chosen as machineable wax and the cuts were made using a two-flute 3.2mm high speed steel end mill. The cutting parameters chosen for this operations are shown in table 2. The commercial Kistler dynamometer is clamped rigidly to the milling machine vise, and the wax workpiece is affixed to the proposed dynamometer using adhesives.

<table>
<thead>
<tr>
<th>Cutting Speed (m/min)</th>
<th>Chip Load (mm/tooth)</th>
<th>Depth of Cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.3</td>
<td>0.05</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 2: Cutting Parameters
From figures 15 and 16 it is shown that both dynamometers accurately represent the process for a tooth passing frequency of 98 Hz. The discrepancy in amplitude between the two is most likely due to the sampling rate limitations. The Kistler dynamometer samples at 5120 Hz allowing for highly resolved cutting force signals while the optical force sensor samples at only 300 Hz creating a much more jagged profile. This limit on the sampling rate was necessary for the proposed optical dynamometer to function correctly. The piezo actuator must remain synchronized to the pulsating laser diodes, following the same scheme as shown in figure 7. Due to some limitations within the internal electronics, the driver circuit of the piezo amplifier experiences small lag compared with the laser diodes. This effect adds up over time, and as the sampling frequency is increased, the two signals begin to diverge rapidly causing errors. In order to avoid these effects, the sampling rate of the proposed dynamometer is limited to approximately 300 Hz to capture the desired cutting force signal without significant deviation.

5 Summary and Future Work

An optical force dynamometer is conceptually designed and implemented in this study. A four-quadrant position sensitive photodiode (PSPD) is used to detect the position of a target surface directly to estimate the applied force/torque in three independent directions. The use of a single detector allows
for the minimization of components and cost to the system, while the novel decoupling algorithm and oscillating detector scheme permits multi degrees-of-freedom measurements without significant performance losses. The system was tested under both static and dynamic loading scenarios and the resulting data was collected and compared to a reference force transducer. This work demonstrates the feasibility of cost effective optical based table dynamometer especially for scenarios where both static and dynamic force measurements are required.

Analysis of the results provides a number of insights into how the dynamometer may be improved. Further work may include additions and modifications to both the hardware and software of the system, including the addition of filtering and compensation schemes, improved amplifier designs, additional degrees of freedom and new applications of the optical force sensor. The forces were not directly output from the sensing system. Instead the direct PSPD voltage signal, due to each of the two laser diodes, was outputted into two separate channels, and the resulting data streams were post processed using computer programs to extract the position and pose information of the target surface and subsequently the applied forces. This method could be improved to allow real-time data streaming with potential applications to machine tool monitoring and force feedback. Signal conditioning was not considered in this study. As the structural dynamics of the sensor body as well as the platform, it is fixed to have a great influence on the frequency response characteristics of the sensor performance, compensation methods could be employed to improve the bandwidth. Disturbance filter designs have been implemented in different transducers to reduce the distortion in the signal due to structural dynamic modes. These filters have the potential to extend the frequency range of the sensor past the fundamental vibration mode and in some cases compensate for the second and third harmonics as well. These filters are commonly based on Kalman filters due to their ease of implementation and quick processing time.

MDOF force measurements are also important as it provide a complete view of the state of an object under loads. The dynamometer developed in this study included three degrees-of-freedom (two translational and one rotational) with the use of two laser sources, a two dimensional triangular prism reflective target surface and a four quadrant photodiode (of which only 2 quadrants were used). This study could be extended to include all six degrees-of-freedom. A proposed layout would include three laser sources, a tetrahedral reflective target surface and a single four-quadrant PSPD. While this system would be highly coupled, a similar analysis could be performed to extract independent position and pose measurements along each measurement direction, and about each measurement axis resulting in the measurement of three force and three torque measurements. The main challenge would be the design and manufacture of an amplifier capable of amplification in each degree-of-freedom.

There are several potential applications of proposed system. Monitoring and adaptive control of machining operations during production using the optical force sensor is a logical extension to this work. An adaptive control scheme could be implemented in micromachining operations, particularly milling operations to maximize material removal while maintaining desired force levels along the tool path. The scheme may also be expanded to include chatter detection through monitoring the power spectrum of forces during cutting and identifying spikes at the tool chatter frequencies. Tool breakage and wear could also be monitored to further improve process control.

References


