AN ANALYSIS OF CRITICALLY ENABLING TECHNOLOGIES
FOR FORCE AND POWER LIMITING
OF INDUSTRIAL ROBOTICS

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AN ANALYSIS OF CRITICALLY ENABLING TECHNOLOGIES FOR FORCE AND
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ABSTRACT

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The power and force limited (PFL) industrial robot market is one that is much underdeveloped and market demand is increasing every year. A literature review of critically enabling technologies for PFL robotics is conducted to evaluate the successes and limitations of developed and emerging PFL technologies. From this analysis a one link robot testbed is developed to test and gain a deep understanding of inherent torque sensing properties. Two custom sensing configurations and two custom torque plates are also designed to evaluate key torque sensing properties. Finally, an evaluation on these results lead to conclusions of the inherent effectiveness of the selected PFL enabling technologies.
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CHAPTER I

INTRODUCTION

1.1 Motivation

Industrial robotics have seen tremendous growth since the first integration of an industrial robot into a factory with GE's use of the Unimate PUMA in 1961 [8]. Since these times robotics technology has exponentially expanded allowing for applications that were deemed not possible to be done by a robot, to become a reality. Classical robotics design features characteristics including fenced workspaces, minimized operator interaction, infrequent task changes, and fixed mounted bases with stiff joints, but the push for robotics into an operator friendly, collaborative environment is a much more underdeveloped market [9]. Just as strides in technology have opened the door for robotics into new environments in the past, industrial robotics research is pushing for robotics success in direct collaboration with humans. According to ABI Research, the collaborative robotics market is a worldwide market that is financially promising with projected sales nearly tripling in two years as shown in Figure 1.1 [1]. Just as past technological advances have increased the scope and efficiency of the robotics industry the collaborative market is working to improve system efficiency including, reduced work cell size, decreased fixturing cost, improved operator safety [10].

For the industrial world, the concept of direct robot/operator interaction is a relatively new concept that has been only recently defined by a global safety standard. The adoption of the ANSI/RIA
15.06 2012, which governs the safe use and design of industrial manipulators for robot manufacturers as well as system integrators provides a framework of new collaboration guidelines. Four categories of documented collaborative modes are outlined, Safety Rated Monitored Stop, Hand Guiding, Speed and Separation Monitoring, and Power and Force Limiting.

This technology analysis will rely primarily on Power and Force Limiting (PFL) as a means for collaborative robot design, and a more detailed understanding of only PFL technology will be provided. The term power and force limiting requires that the power and force output of the robot must not exceed an unsafe value. This limiting of power and force can be achieved by either inherent design or control methods, which are not limited to but include technologies such as joint torque sensing, series elastic actuators, padding, and impedance control [10]. It is important to note that the definition of power and force limiting is dependent upon the specific application and the associated risk assessment of the overall application.

It is important to understand the fundamental differences and advantages that power and force limiting offer as separate methods of analysis. When a robot is performing a task in which external application forces are being applied to the robot, many times there are very clear acceptable force
ranges. For example, testing with sharp tools mounted to a robot was done by DLR. It was determined that for a specific tool a very specific range of contact force was deemed either acceptable or unacceptable. In fact, by monitoring these external forces with a specific control setup, DLR was able to demonstrate a robot with a sharp edged tool colliding with a human arm with no punctured skin [11].

Another approach is to power limit a manipulator to achieve power and force limiting. Rather than determining the control system output of applied force as done with the DLR sharp tool testing, the robot actuators can be designed with a low power input. If the robot actuators are designed for low power it is simply not possible to have a high force output. An application this could be more applicable for than consider force limiting is a collaborative environment where it is expected for the operator to make contact with the robot at unstructured instances in time. A valid risk assessment methodology could be to rate the actuators to a low enough power that there is not a control situation in which the operator could be harmed from impact. Of course the risk assessment would need to consider other hazards such as being pinched by the robot or sharp edges [12].
A literature review of nine critically enabling PFL technologies was conducted to summarize the current state of the industrial and research worlds use of these technologies as well as the advantages and limitations of each. These technologies are divided into 2 sections, PFL Sensing Configurations, Evaluation of PFL Sensing Configurations.

2.1 PFL Sensing Configurations

Many unique configurations have been researched and implemented to measure applied loads to a robot including joint torque sensing, Series Elastic Actuators, 6 DOF F/T sensors, and skin technologies.

2.1.1 Joint Output Torque Sensing

Traditional industrial robot design requires actuators with high gear reductions, typically 1:100 or 1:160 because of the significant torque requirements of the robot. For this reason, direct drive robots are very uncommon in the industrial world and most designs incorporate strain wave gearing. The addition of these gear trains create nonlinear friction forces which are very difficult to model [37]. For over twenty years torques applied at each joint have been estimated by measuring each motor current to calculate the applied torque. While very sophisticated modeling of friction forces has been accomplished with satisfactory results, this method is limited. With the inclusion of torque
sensors at the output side of the strain wave gearing a much more accurate calculation of applied
torque is possible, as it is after the gear train losses and no friction compensation calculations are
required.

i) Piezoresistive: Strain Gauge

Strain gauges rely on a coiled trace of conductive material which can be used to calculate uni-
axial strain of a deflected beam causing a change in resistance. This change in resistance/strain is
proportional to the applied torque [13]. This technology is advantageous because if properly applied
can very accurately measure applied torque with resolutions in the order of 0.001 strain [14]. Strain
gauge technology is also one of the most commonly used force/torque sensors in the industrial
world, meaning that a significant research base and commercial off the shelf strain gauge products
are readily available. However, strain gauges also have significant limitations. Of particular concern
is the robustness of the technology. Not only must the sensor be installed/adhered by a skilled
technician but the inherent fragile trace sensor design makes the sensor susceptible to deflection
beyond yield strength. Also a limitation of the trace design is extreme sensitivity to temperature
changes in the environment. Strain gauges output very small changes in resistance and typically
the output signals must be conditioned and amplified for meaningful interpretation. This signal
conditioning means the sensor is particularly susceptible to noise at the sensor as well as introduces
a significant amount of signal processing hardware, increasing not only cost but complexity of
mechanical and electrical design.
ii) Optical

Optical torque sensing typically relies on a combination of LEDs and photodiodes which can measure the angular displacement between two plates. Using basic mechanical engineering principles this angular displacement can be used to calculate the applied torque [15]. As optical sensing has very high resolution, some sensors requiring 0.001 angular deflection or less for accurate torque calculations, allowing for a mechanically stiff arm to be designed [16][17]. As optical measurement is the means of measurement it is possible to design a sensor such that it is optically isolated from sources of EMF noise [16]. Typically optical torque sensor will use a coded blind that is decoupled from either the actuator output or link. This coded blind ring is mechanically limited by mechanical boundary conditions including but not limited to the bearing [3].

iii) Magnetostrictive

As particles of a magnetostrictive material are subject to a magnetic field the opposite poles of adjacent particles align, thereby increasing part length and inducing strain [18]. This principle is illustrated in Figure 2.1 which shows an example magnetostrictive torque sensor setup. As a torque is applied to the magnetostrictive material an axial change in magnetic field intensity is measured by the Hall Effect sensor [19]. Hall Effect sensors only output a voltage relative to an axial direction, magnetoresistive sensors output a voltage relative to the angle of the sensor plane and magnetic field [20]. An efficient design of a magnetostrictive sensor would likely include the combination of both Hall Effect and magnetostrictive sensors [21].

This technology has seen industrial success for many years in applications such as sensing applied torque to a steering column [19]. As measuring electric field via a hall effect/magnetoresistive sensor does not require contact to the applied torque therefore a very robust sensor integration can be designed [21]. However, magnetostrictive sensing depends on defined environmental conditions
including temperature, air gap distances, and varying sources of environmental EMF noise. Mechanical design considerations such as allowing for proper air gap distances between rotating shaft and sensor also could cause undesired overall design size [19]. Yet another limitation is the material constraint that the rotating element must be of a magnetostrictive material [3].

iv) Electrostatic Capacitive

At the simplest level a capacitive sensor is used to measure capacitance between two plates as a function of separation distance, separation medium, and effective plate area. For torque sensing applications, a capacitive sensor is used to output a dynamic voltage by the varying distance from the opposing electrode plate [22]. Basic design of capacitive torque sensors typically have an array of electrodes on the input shaft. These electrodes will likely have the same input oscillating signal, however as seen in Figure 2.2 each of the four electrodes are 90 out of phase, with the phase pattern repeated four times (16 rotor electrodes). As the number of total electrodes within reasonable mechanical spacing are added to the system the measurement resolution will increase. A capacitive
sensor is then mounted a given distance from the electrodes allowing for a measurable twist angle to be measured upon applied torque [3]. In the application of measuring torque of a motor, the capacitive sensor would be mounted to the stator as seen in Figure 2.2, likewise in a robotic application the sensor would be mounted to the output link.

![Figure 2.2: Basic Capacitive Angular Displacement Sensor for Rotor-Stator [3].](image)

Note that a basic design has been described, however many other design configurations are seen through the industrial and research world. Because capacitive torque sensing does not require contact to the rotating input a very robust and ultimately simple design is possible [3]. Just like many of the previous sensors, as capacitive torque sensing is non-contact and rugged design is made possible.

### 2.1.2 Mechanical PFL: Series Elastic Actuators and Variable Stiffness Actuators (SEA and VSA)

PFL sensing can also be achieved using methods of controlled mechanical compliance. This is an area of research that has received much attention and has even seen industrial implementations.
i) Series Elastic Actuators (SEA)

SEA provide a mechanical solution to force and power limiting and is seen in a wide array of implementation, however two commons implementations are seen in Figure 2.3. Compared to traditional stiff robot actuators and in the case of industrial robotics, SEA designs utilize an elastic element in series with the servo actuator [4].

![Figure 2.3: FSEA and RFSEA Models [4].](image)

If the deflection of the elastic element is measured the applied force can be calculated by using Hookes Law as a base model. These deflection measurements turn each joint into a joint torque sensor that has increased mechanical compliance which can limit the applied force. However, this method of force and power limiting has inherent limitations. The motor in series with the elastic element is also deflecting the spring, creating a more complicated calculation to isolate external forces. This design scenario also suffers when forces are applied at the resonant frequency of the actuator because applied forces cannot be tracked [4]. Testing has been completed by DLR that shows that mechanical compliance in the form of SEA does not reduce the impact force to those seen with traditional stiff robotics design. This same testing also revealed that SEA designs can unsafely store and release energy in periods of high acceleration motion [23].
ii) Variable Stiffness Actuators (VSA)

VSA can dynamically vary the mechanical stiffness of the actuator by using various actuation methods. An example of this concept can be seen in Figure 2.4 which utilizes a small motor to vary the spring stiffness of a torsion spring attached the circular spline of the actuators harmonic drive [5].

![Figure 2.4: Circular Spline of Harmonic Drive Supported by VSA Mechanism [5].](image)

A significant advantage of VSA actuator design is that mechanical compliance is used to elastically decouple the link from the actuator to protect the joint during periods of external overload. A similar concept shown by Boston Dynamics research which intends to achieve a running motion makes use of varying the spring stiffness of the actuator to mechanically store energy at very specific points in time and release the stored energy also at very specific times (ie. when speed bursts are needed) [5]. However, as soon as additional actuators are included in a robot design, complexity and cost must increase, both on the mechanical and electrical design. Another inherent limitation of VSA is that with variable values of joint stiffness it is likely that a reduction in absolute accuracy would be seen [5].
2.1.3 6 DOF F/T Sensing

A 6 DOF Force/Torque sensor is designed to measure all three forces and three moments about the sensor. These sensors typically feature a ring shaped design with very specifically designed radial rings. Typically, strain gauges are mounted to these radial rings in specific orientations to calculate the required force and torques [24][25]. As a torque is applied to the ring design the radial beams experience deflection and is measured by whichever type of sensor may be mounted. This sensor deflection data is used to calculate the F/T output signals, allowing the robot to switch from a less flexible position control to a more dynamic force feedback control system.

i) 6 DOF F/T Sensing at the End of Arm (EOA)

EOA of F/T sensing requires that a 6DOF F/T sensor be placed between the last link and the end effector. This mechanical placement allows for direct F/T measurements of the application process wrench. While the sensor output strain will be given relative to the sensor location, with known tool design information the force and torques measured can be transformed relative to the tool. As the tool is what is physically making contact with the external world in most cases this is the most relevant process force data [24].

Successful implementation of this technology has been seen all over the world in both the research and industrial industries. For example, in the DLR-Hand II, miniature 6 DOF F/T sensors were developed which were mounted to each finger of the hand to receive F/T feedback on a per finger basis [14]. As this sensing technology is the most direct method of measuring process force at the EOA, this is naturally a critically enabling technology for not only force and power limiting but also hand guiding. However, this sensing methodology does have inherent limitations including the clear statement that applied forces to any part of a robot before the F/T sensor cannot be accurately measured. This is problematic in a collaborative environment because an operators safety cannot be guaranteed with EOA F/T sensing alone [26]. As the sensor is mounted at the EOA all power and
data cabling must run through the entire arm to reach the controlling device. Increased cable length and cable motion can cause issues including high noise environment and lack of robustness [27]. Also noteworthy is the scalability of this technology with increased tool mass. Even though it has been assumed that collaborative robots will generally operate at lower payloads, as the tool mass increasing the accuracy and response time of the F/T measurements will be reduced [28].

ii) 6 DOF F/T Sensing at Robot Base

6 DOF F/T sensors have also been implemented by mounting between the robot base and table/ground surface. This sensing technique, shown in Figure 2.5, has been labeled as Base Sensor Control (BSC) by researchers at MIT who are doing the majority of the published research on this topic [2][29][30].

Figure 2.5: Serial Manipulator Mounted on Base F/T Sensor [2].

Friction forces in a highly geared manipulator have been research struggle for years because of the significant nonlinearity associated with these friction forces. Gear train friction is a function of joint position and forces such as Coulomb friction, static friction, load, and temperature changes.
which are not trivial to measure [31][2]. These complex dependent variables are magnified in partic-
ularly high friction applications, take for example a large payload robot operating at low speeds.
Traditional force feedback using methods such a motor current to calculate applied torque fail to
accurately and reliably measure applied external forces/torques [2][14].

The inherent advantage of the BSC configuration is that by mounting the F/T sensor beneath
the first link the measured F/T data is independent of all internal joint friction forces. Because the
sensor is mounted to the robot base, only net forces and torques are measured, joint/transmission
friction forces are not measured because they are internal forces [2]. Using analytic techniques
such as least-squares method the individual joint torques can be calculated using the known joint
kinematics and inertial data from the base F/T sensor [30]. Because the sensor is mounted to the
beneath the first link, sensor assembly is simple compared to other torque sensing alternatives.
There is no need to manage cabling through the arm of the robot as well that a base sensor may
not be specifically designed for one robot model. It is very likely a base F/T sensor design could
be manufactured that accommodates many robot models/manufacturers [32]. Experimental testing
done with a PUMA robot by MIT scientists have proven that this a technically feasible technology
and that robot dynamics can be estimated well. Future work regarding increased degrees of freedom
and more specific torque estimation accuracy must be done [30].

2.1.4 Skin Technologies

An alternative sensor solution to enable PFL to those presented include the use of skin tech-
nologies. The term skin is used to infer that sensors are mounted along the surface area of the
robot to detect external obtrusions as seen in Figure 2.6. Skin technologies include sensing meth-
ods using a range of sensing methods including capacitive, inductive, optical, acoustic, and optical
[6][33]. These sensors can be used for many unique detection strategies, however proximity and
tactile sensing will be focused on. In order to achieve power and force limiting a control scheme
could be developed which simply stops the robot when a proximity maximum range is violated. With the development of tactile skin sensing, PFL could certainly be achieved by measuring applied external force at every location on the outside of the robot.

Figure 2.6: Skin Technology for Whole Arm Obstacle Avoidance [6].

i) Capacitive Skin

The capacitive skin technology relies on the basic capacitor design principle. It is given that there are two electrode plates with one acting as the transmitter and is provided an input voltage, the second electrode plate is the receiver which can be used to measure changes in EMF or capacitance in an evaluation circuit. An example of this is seen in Figure 2.6 which shows the use of change in EMF to measure proximity and change in capacitance to measure applied force [34]. The obvious
appeal to this technology is that by covering the entire arm in such a capacitive array, entire arm sensing can be achieved, regardless of arm orientation.

### 2.2 PFL Sensing Configuration Evaluation

Power and force limiting can be accomplished with many different sensing technologies, however understanding the inherent advantage and limitations of each technology against one another is critical for an effective evaluation. A graphical cross-technology analysis is seen in Table 2.9 which analyzes the form factor and sensing qualities of the sensing technologies previously discussed. All sensing technologies were analyzed from a general application viewpoint, in that the most ideal technology would perform in nearly all applications.

**Size/Weight**
Figure 2.9: PFL Technology Design Form Factor Analysis Matrix.

Critical design characteristics of a collaborative robot must include a geometrically efficient and light weight manipulator. An efficient design would include minimal modifications to the mechanical system of a robot but also the kinematics and dynamics. A lightweight and small sensor package would satisfy these requirements [35]. It is seen in Table 3.3 that all joint output torque sensing methods (strain gauge, optical, magnetostrictive, and capacitive) are rated adequate for both size and weight. All enabling sensors are relatively lightweight and while mechanical alignment would vary from sensor to sensor slightly, weight considerations would be very similar. As demonstrated by recent research publications from the robotics industry, all four technologies would likely make use of a joint output ring which would mount the sensor and measure relative angular displacement at the joint [35]. Size and weight of these rings would be minimized and of similar scale from sensor to sensor. It has been shown in both the research and industrial world that size and weight constraints of SEA and VSA designs are adequate. While compact and relatively lightweight designs have certainly been accomplished in the most passive SEA designs, it has been shown that
the most successful designs require additional hardware to vary mechanical stiffness. Additional mechanical considerations including actuators, gear trains, and multiple elastic elements must all be considered as an undesirable addition to the overall design size and weight [5]. The remaining three technologies of 6 DOF F/T at the end of arm and robot base, and capacitive skin sensing all add minimal size because of obvious mounting location benefits.

**Cable Management/Modular**

In an attempt to develop a simple and efficient means of power and force limiting the design and implementation must be modular and scalable in nature as well as minimize problematic and expensive internal cabling [9]. All torque monitoring methods are deemed poor for cable management and are difficult to adequately address because the torque sensing is located at specific joints on the arm and the accompanying cabling must be routed through the entire arm to the sensing location. An ideal design would minimize these cables through a bus communication protocol as demonstrated with the DLR LWR-III lightweight robot [36].

It is possible to achieve passive PFL through inherent mechanical SEA design internal cabling could be adequate, even though force feedback would require sensors for spring deflection, which does not escape the problem of internal cabling. Considering VSA/SEA, particularly if a joint is designed to utilize the key mechanical advantage of storing kinetic energy, dramatically unique design for each joint must be developed, creating a model of poor modularity. This is illustrated in examples including the varying degree of joint design of NASAs Robonaut 2 to the focused energy storage at specific joints seen in Boston Dynamics running prototype [37][38][39].

**Installation, Maintenance/Robustness/Complexity**

Strain gauges and VSA have poor ease of installation and maintenance due to the complex nature of each sensor. Strain gauges are a thin membrane that must be pretensioned, properly located, and adhered by a skilled technician [40]. Strain gauge maximum allowable strain is very near the
strain gauges yield strength, requiring mechanical overload protection to guarantee protection of the sensor. Even with a material change to a silicon semiconductor the transducer still outputs a low voltage signal which will need amplified/conditioned before being processed leaving an opportunity of sensitivity to electrical noise [35]. While control strategies have been implemented to improve temperature sensitivity, overall strain gauges have room for improvement for robustness.

Optical, magnetorestrictive, and capacitive solutions all offer similar attributes for installation/maintenance because all are joint level solutions. An advantage of magnetorestrictive installation is that the calibration can easily account for small mechanical misalignments, however, capacitive and optical sensors are more sensitive to radial displacement and more difficult to calibrate and are therefore stricter on sensor mounting locations. All three sensing technologies provide robust solutions as they can measure angular deflection without contact [35].

When analyzing the robustness of capacitive skin technologies it is difficult to practically implement at this point in time. While pretouch sensing does not require physical link deflection to stop for a foreign object, it is difficult to distinguish between an approaching human operator and perhaps a new cell jig. Research examples have been shown with whisker designs or lattice arrays, however a robust skin surface mounted design has significantly less available research with robust solutions than other power and force limiting technologies [6][41][42][43].

More quantitative sensor characteristics seen in Table 2.10 are another important analysis tool for properly evaluating PFL technologies. All ranking was scored by examples seen in the industrial and research world that exhibit developed technology.

By combining the results in Tables 2.9 and 2.10 a further analysis of the practicality of future development can be assessed. SEA has certainly been used in power and force limiting applications in the robotics and research/industrial world in the past. However, the mechanical elasticity introduced to the arm creates a very unique set of strengths and limitations. Many of the difficult
modeling problems in the robotics world stem from modern robots being highly geared to achieve the high torques required. By introducing a series elastic element after or before the geartrain output the maximum torque output of the link is greatly reduced. It is therefore determined that while SEA has a definite value and unique solution to PFL, it does not simply address PFL on a highly geared robot. In order to create a repeatable robot featuring SEA, the mechanical and control design must become very complex to accommodate for the added elasticity. Reduced repeatability of an arm is a very limiting factor in suitable applications and does not allow for the optimal design of a collaborative robot. It is believed that SEA may be a technology better suited for direct drive, lower torque robotic applications.

The analysis of VSA is similar to SEA in that overall design complexity must be significantly increased. The inherent advantage of VSA is that the high torque output of a robot can be taken
advantage of when it is needed as well as utilizing a more compliant mode when in a collaborative environment. However, this added flexibility over SEA comes with the price of significant complexity. VSA research at this time requires an additional actuator to adjust the joint compliance. Therefore, if VSA were to be used on a 6-axis manipulator the entire system actuator count would at least double creating significant mechanical, electrical, and control complexities.

Of the many skin technologies introduced, capacitive sensing was focused on. Capacitive sensing offers benefits none of the other discussed methods offer, including perhaps the most attractive of pre-touch proximity sensing. The skin technologies in general allow for the robot to anticipate a collision with an external object. As compared to other torque sensing which requires a reactive physical joint deflection post-touch, skin technologies offer a more proactive approach. Capacitive skin research has shown successful proximity sensing and force feedback post-touch. However, these technologies have not shown the maturity of development other sensors have. While capacitive proximity sensing offers a potential solution for PFL, it is deemed a not optimal solution because of practicality concerns.

6 DOF F/T sensing provides a very encouraging PFL technology that has been proven in the research and industrial world for many years. Particularly when regarding end of arm mounted F/T sensors, many commercial off the shelf solutions have been developed and have performed well. It has also been well proven that a 6DOF F/T sensor is going to measure forces at the EOA very accurately, much more accurately than many other sensing techniques. Traditional robot design assumes a robot to be operating in a periodic sequence of repeated tasks, however this analysis is not focused on PFL for robots in collaboration. Therefore, while an F/T sensor at the EOA performs adequately with traditional robotics, the sensor does not achieve effective whole arm PFL in a collaborative environment. Note that this analysis does not include any complementary sensors and possible beneficial sensor combinations certainly exist.
The same 6 DOF F/T sensor mounted between the last link and the mounting surface provides the simplest solution to PFL that has been analyzed. Because the sensor is external to the robot, no through arm cabling routing must be accounted for, also meaning a traditional manipulator could be used for PFL development. With the sensor being mounted external to the robot only external output forces are measured, meaning no complex geartrain friction modeling must be accounted for. Friction has been a difficult problem in robotics for years and these combination of advantages proposes a simple, effective solution. However, there has been very limited published work on 6DOF base F/T sensing and development certainly must take place to better understand how effective this method would be compared to torque sensing at every joint.

It is well known that measuring torque at the output of the gear train yields a very direct measurement that can be used in a range of applications including passive control design, gravity compensation, vibration damping, and sensitive collision detection [36]. While all other sensing capabilities can be used to varying degrees for similar applications, joint output sensing clearly provides the most dynamic and responsive control system for the entirety of the arm. If key limitations such as joint stiffness, size, and cable management can be minimized in the design process joint output torque sensing provides a very promising means of power and force limiting.

Although torque sensing has been historically achieved in the robotics world most frequently with strain gauges, it is not believed to be the optimal PFL solution. Significant issues relating to the robustness of strain gauges is limiting to industrial, practical use. Strain gauges have certainly been proven to function industrially in successful projects including NASA Robonaut 2 and the Kuka IIWA [44] [45]. However, a simpler, more robust solution is desired. The results summarized in Tables 2.9, 2.10 indicate that two other joint output torque sensor types, capacitive and optical, provide equivalent or better sensing capabilities compared to strain gauges. While performance of capacitive and optical sensors have been proven to be adequate for robotics, they also feature
very useful design features including non-contact measurement and better performance in dynamic environments which yield increased robustness. The relative ease of installation and maintenance of optical/capacitance torque sensing compared to strain gauges can also not be ignored. For these reasons it is determined that optical and capacitive torque sensing at the output of the gear train prove to be the most promising and effective sensor technology for future PFL collaborative robot development.
CHAPTER III

TESTBED EVALUATION

A custom one-link robot testbed was designed and manufactured to facilitate the torque sensing technology analysis. This testbed will be detailed throughout Chapter 3.

3.1 Mechanical System

The testbed’s mechanical system comprised of a thru-bore AC servo actuator, Harmonic Drive reduction, custom torque plate, and an extension arm to represent a robot link.

3.1.1 Torque Plate

A radial beam torque plate was designed to allow a torque applied on the external link to cause a mechanical deflection at the torque plate. The inner diameter of each torque plate was rigidly mounted to a robot servo while the outer ring diameter was rigidly mounted to the robot link being driven by the servo. Two torque plates, shown in Figure 3.1 were designed to offer unique performances. Torque Plate 1 followed traditional industrial robotics practice and utilized a more stiff deflection plate which allowed minimal deflection. As an alternative, Torque Plate 2 offered a much less stiff plate with increased allowable deflection.

Both torque plates leveraged design practice insights gained from research presented in Chapter 2. Mechanical overload of the sensing plate is critical because if the radial beams are exposed to a torque greater than allowable, the beams will yield causing a failure. Significant FEA was conducted
to select beam geometry and material to obtain the desired beam deflections. Figure 3.2 shows 4 pockets milled out of each torque plate which allow for free deflection of the radial beams for a designed torque threshold. After the torque threshold was crossed the inserted steel tab will bear the load from inner diameter to outer diameter, thereby protecting the radial beams from excessive torque loading in the designed load bearing plane. Also note that the tab and torque plate are designed to provide a mechanical overload for any out of plane loading. While a simple design, this torque overload tab concept is novel because it provides overload protection in all loading directions as well as yields a simplified method of installation/maintenance as compared to alternate design examples discussed.

Each plate was designed with a unique spring stiffness value as shown in Table 3.1. Traditional robotics which has seen much success in the last 30 years is typically implemented with stiff, repeatable robot linkages. However, as already presented much research is being focused on ’soft
Table 3.1: Torque Plate Mechanical Comparison.

<table>
<thead>
<tr>
<th>Material</th>
<th>Max Deflection $\delta$ (mm)</th>
<th>Spring Stiffness $k$ (Nm/deg)</th>
<th>Max Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Plate 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum (6061-T6)</td>
<td>0.165</td>
<td>234</td>
<td>$\pm 75$</td>
</tr>
<tr>
<td>Torque Plate 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless Steel (17-4 PH)</td>
<td>1.01</td>
<td>38.3</td>
<td>$\pm 75$</td>
</tr>
</tbody>
</table>

Figure 3.2: Mechanical Protection for Torque Overload.

robotics’ which requires lower spring stiffness value. These different implementations of torque sensors are represented by the unique spring stiffnesses shown in Table 3.1.
3.2 Electrical System

The electrical system of the testbed consisted of two custom sensing configurations and the data acquisition hardware/software required for implementation.

3.2.1 Sensors

As shown in Table 3.2, two sensors were selected for testing given the results of the sensor review previously discussed. A Micro-Epsilon CSHA2FL-CR15 high-resolution capacitive sensor was used to measure linear beam deflection of the torque plate. This sensor produces a 0-10VDC analog output with a measuring range of 1.0mm and resolution of 0.025um. A Broadcom AEDR-8710 optical encoder was used as the second sensor to detect angular deflection. A custom reflective codewheel was designed to accommodate torque plate design. This codewheel featured a line density of 318 lines/inch and 16x interpolation for highest allowable resolution.

Table 3.2 reveals a clear performance vs cost contrast between both sensors offered and will provide an excellent analysis tool to compare results against. Also note that both sensors provide industrially common sensor input and required power inputs and achieve this in a small geometry sensor package.

Table 3.2: Sensor Mechanical Properties Comparison.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Brand/Model</th>
<th>Geometry LxWxH(mm)</th>
<th>Weight (g)</th>
<th>Cost (USD)</th>
<th>$V_{IN}$ (VDC)</th>
<th>Output Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive</td>
<td>Micro Epsilon</td>
<td>20.0 x 20.0 x 5.0</td>
<td>50</td>
<td>˜1500</td>
<td>9-36</td>
<td>Analog 0-10</td>
</tr>
<tr>
<td></td>
<td>CSHA2FL-CR15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Broadcom</td>
<td>4.0 x 3.4 x 1.0</td>
<td>1</td>
<td>˜15</td>
<td>3.3-5</td>
<td>Single Ended 5VDC Quadrature</td>
</tr>
<tr>
<td>Encoder</td>
<td>AEDR-8710</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3: Sensor Properties Comparison.

<table>
<thead>
<tr>
<th>Sensing Technology</th>
<th>Brand/Model</th>
<th>Resolution at Sensing Face</th>
<th>Operating Temperature Range(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive</td>
<td>Micro Epsilon CSHA2FL-CR15</td>
<td>0.025µm</td>
<td>5-60</td>
</tr>
<tr>
<td>Optical Encoder</td>
<td>Broadcom AEDR-8710</td>
<td>0.079mm</td>
<td>-20-85</td>
</tr>
</tbody>
</table>

3.2.2 Robot Link Assembly

A Yaskawa SGAGS-761KA2A-YR11 servo actuator with max rated torque of 75Nm was used for testing. This servo featured a built in Harmonic Drive geartrain with reduction of 1:101. Note that this packaging of servo and Harmonic Drive allow for very compact geometry with high reduction ratio, zero backlash, and a through hole for internal cabling are enabling design features for a torque controlled actuator to be built into a robot. This servo was rigidly mounted to a test fixture as shown in Figure 3.3. As discussed in 3.1 the Torque Plate was mounted directly to the output of the Harmonic Drive, mechanical overload tabs were then inserted, to be finally assembled with a simple robot link extension.

To complete testbed assembly the sensor equipment was added as shown in Figure 3.4. Note that the left portion of the Figure 3.4 illustrates the steel ‘flag’ which is rigidly fastened to the inner diameter of the torque plate. Therefore the ‘flag’ will rotate with respect to the output of the Harmonic Drive. The capacitive sensor is then rigidly mounted to the outer diameter of the torque plate, therefore capacitive sensor will rotate with respect to the output of the Harmonic Drive + beam deflection caused by an external load.
As shown in the top of Figure 3.4 the optical encoder mounting is shown. Similar to the capacitive sensor the optical encoder head is rigidly mounted to the Torque Plate inner diameter, while the reflective codewheel is rigidly mounted to the Torque Plate outer diameter.

Table 3.4 illustrates a resolution comparison between the tested sensors. It can be seen that the resolution provided by the capacitive sensor is roughly one order of magnitude larger than that provided by the optical encoder for both torque plates. Considering that both torque plates are designed for a max rated torque of 75Nm, it is clear that the resolution of the optical encoder is much less desirable than that of the capacitive sensor.
### 3.2.3 Data Acquisition

All data was collected using an Allen Bradley ControlLogix PLC and respective IO cards. An external load cell was used to measured the applied load. This load cell was located at a known distance along the robot link so that applied torque could easily be calculated from an external source. The load cell was a Shimpo DFS-100 with 0.1N resolution, 0-500N measuring range, and 0-10VDC analog output. The capacitive sensor mounted to the Torque Plate and external load cell were wired directly to the PLC Analog Input card with a 16bit A/D conversion and configured for 0-10VDC analog input. The optical encoder was wired directly to a High Speed Counter card capable of measuring the 5V TTL singed ended quadrature encoder output.

As shown in Figure 3.5, a ControlLogix PLC was the interface to all external sensing devices. A Control PC was able to communicate with the PLC via Ethernet/IP to record and process all sensor data using MATLAB. The Control PC was also able to communicate via Ethernet/IP to a motion planning PC which commanded the Yaskawa SGDV-3R8AE1A amplifier a motor position.
Figure 3.5: System Layout.

Table 3.4: Measurable Sensitivity Comparison.

<table>
<thead>
<tr>
<th></th>
<th>Spring Stiffness $k$ (Nm/deg)</th>
<th>Optical Encoder (Nm/pulse)</th>
<th>Capacitive (Nm/step)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Plate 1</td>
<td>234</td>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>Torque Plate 2</td>
<td>38.3</td>
<td>0.16</td>
<td>0.019</td>
</tr>
</tbody>
</table>

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CHAPTER IV

TORQUE ESTIMATION EXPERIMENTS

In order to fully understand the critically enabling technologies for power and force limited robot the reduction system must be investigated. Harmonic Drives are common to the robotic industry for many reasons and three primary sensing contributions from the Harmonic Drive reduction will be evaluated. Upon understanding the properties introduced by a Harmonic Drive reduction a more direct sensing comparison between the optical encoder and capacitive sensor will be evaluated.

4.1 Harmonic Drive

A Harmonic Drive gear reduction is very specifically designed to offer desirable operating conditions in a robotic application. As shown in Figure 4.1, a Harmonic Drive is comprised of three major components. The input motor shaft is attached to the wave generator which consists of a raced ball bearing built in an elliptical shape. The Flexspline is a thin walled component which will allow for radial deformation but very resistant to torsion. The Wave Generator is inserted inside the Flexspline and the Flexspline then conforms to an elliptical shape. Finally, the Circular Spline is very rigid with teeth on it’s internal diameter which assemble and mate to the Flexspline teeth.

Figure 4.2 shows a graphical representation of how these Harmonic Drive components work together to yield an effective reduction. The Wave Generator defines the elliptical shape of the input drive mating with the Circular Spline in two opposing regions. Because the Circular Spline has two
more teeth than the Flexspline, every 180 degrees of input rotation from the Wave Generator yields a one tooth rotation between Circular Spline and Flexspline. This design offers many inherent advantages including high reductions ratios with reduced geometry, excellent repeatability with inertial loads, and theoretical zero backlash.

While the Harmonic Drive offers impressive and unique torque transmission properties, (3) well understood phenomenon must be understood for a comprehensive analysis. These properties will
be discussed in the subsequent subsections and include torque ripple, nonlinear spring stiffness, and hysteresis.

4.1.1 Torque Ripple

The design of the Harmonic Drive yields one tooth to advance between the Circular Spline and Flexspline every 180 degrees of input rotation. This meshing of teeth causing a phenomenon known as Torque Ripple on the output device. Torque Ripple occurs at a known frequency of 180 degrees of the input Wave Generator and is irrespective of applied torque [46].

To investigate the effect of Torque Ripple, Torque Plate 2 was dynamically loaded from 0Nm-45Nm to evaluate measured torque via capacitive sensor vs actual torque with the external load cell and results are shown in Figure 4.3.

![Figure 4.3: Torque Plate 2 Slow Impact Measured Torque](image)

Upon further investigation, both the capacitive sensor and external load reveal slight steps every 0.45s. Figure 4.4 takes a closer look at this concept as a zoomed in plot of Figure 4.3. Given the
speed of the servo and reduction of the Harmonic Drive, the time in seconds between each teeth of
the Harmonic Drive was calculated and the orange step function overlaid in Figure 4.4 represents
every rotation of 180 degrees of the input motor. It is clear that the small constant frequency distur-
bances measured by both sensors is caused by the meshing of teeth in the Harmonic Drive. While
this is a well documented phenomenon of Harmonic Drives, it is clear from a literature review that
manufacturing processes improvements have significantly reduced amplitude of disturbances since
the infancy stages of robotic Harmonic Drives [47].

![Figure 4.4: Torque Plate 2 Slow Impact Harmonic Drive Teeth Mesh.](image)

### 4.1.2 Nonlinear Spring Stiffness

The torque sensor system used in this study incorporated a near linear spring of the designed
torque plate which was mounted to the Harmonic Drive reduction spring in series. It is well known
that the Flexspline of the Harmonic Drive creates a non-linear spring stiffness. The servo motor was
requested to push the robot link against a stiff object slowly and record torque sensor output. Col-
llecting known forces and angular offsets, the spring stiffness was calculated at the various torques
and shown in Figure 4.6. It can be seen that at low torques of 0-5Nm the spring stiffness exhibits a linear trend, however after applying torques greater than 10Nm the spring stiffness becomes non-linear. Many simple modeling strategies have been successfully implemented including a piecewise linear approximation as documented by the manufacturer ([48])([49]).

![Joint Stiffness vs Measured Torque](image)

**Figure 4.5: Torque Plate 2 Spring Stiffness vs Measured Torque**

It is clear that the spring stiffness from 0-5Nm yields a significantly smaller spring stiffness than the rest of the rated torque curve. This is a well understood phenomenon known as Soft Windup. Soft Windup is a region near zero torque in the positive and negative direction which yields an angular output near zero [96].
4.1.3 Harmonic Drive Hysteresis

As the Flexspline introduces a non-linear spring stiffness and Soft Windup section at low torques an inherent hysteresis is introduced. Testing was completed by beginning with no load on the torque sensor, loading to near max rated torque and returning back to no load. Figure 4.6 shows the results and the expected hysteresis is illustrated. As documented by the manufacturer Harmonic Drive this behavior is expected and will be measurable at +/- 4 percent of rated torque. The hysteresis displacement of approximately 2Nm shown in Figure 4.6 is very near the expected value as the reducer that was tested is rated at a max torque of 75Nm. [7].

Figure 4.6: Torque Plate 2 Static Loading.
Table 4.1: Torque Sensor Resolution Comparison

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Model</th>
<th>Rated Torque (Longitudinal Axis) (Nm)</th>
<th>Resolution (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATI Torque Sensor</td>
<td>Omega85 SI-1900-80</td>
<td>40</td>
<td>0.0047</td>
</tr>
<tr>
<td>Torque Plate 1</td>
<td>Capacitive Sensor</td>
<td>50</td>
<td>0.110</td>
</tr>
<tr>
<td>Torque Plate 2</td>
<td>Capacitive Sensor</td>
<td>50</td>
<td>0.019</td>
</tr>
<tr>
<td>Torque Plate 1</td>
<td>Optical Encoder</td>
<td>50</td>
<td>1.0</td>
</tr>
<tr>
<td>Torque Plate 2</td>
<td>Optical Encoder</td>
<td>50</td>
<td>0.16</td>
</tr>
</tbody>
</table>

4.2 Sensor Comparison

Now that an understanding of the Harmonic Drive contributions to torque sensor output have been discussed it is needed to better understand the performance of the two selected sensing technologies.

In order to gain insight on appropriate resolution for a torque controlled robotic application Table 4.1 illustrates an industrially accepted and commonly used robotic torque sensor produced by ATI as compared to the optical encoder and capacitive sensor used in testing. Also compared are the Torque Plate 1 and 2 because of the differing spring stiffnesses, varying sensor resolutions are reported.

Figure 4.7 shows a direct sensor output comparison for the same loading condition. It is very clear that the capacitive sensor tracks the actual torque very closing and the optical encoder not only has a very coarse resolution but does not track the actual torque as effectively. The capacitive sensor yielded an average error of 0.34Nm while the optical encoder an average error of 3.4Nm. As shown in Table 4.1 the optical encoder was advertised with a resolution of 0.16Nm, however Figure 4.7 shows an effective minimum resolution of 2Nm.
Figure 4.7: Torque Plate 2 Sensor Comparison.
CHAPTER V

CONCLUSIONS

Successful sensory implementation of a power and force limited industrial robot must include an analysis of all components that have been discussed. It is critical to not only understand the successes and limitations experienced by others and discussed in Chapter 2 but also to gain personal insight by evaluating similar technologies in the testbed results. In this section the two sensing technologies selected for evaluation will evaluated for performance and usability.

5.1 Capacitive Sensor

The Micro Epsilon CSHA2FL-CR15 capacitive sensor provided an excellent displacement measurement device. At a compact form factor of 20x20x5mm and rugged industrialized casing the sensor could be reasonably installed and maintained while mounted locally in a robot joint. This is overall a very simple sensor to integrate as 16 bit analog inputs are industrially commonplace and reasonably immune to electromagnetic interference and temperature stability. As the sensor is capable of measuring displacements as small as 0.025um or 0.019Nm for the testbed configuration this provides an adequate resolution. As compared to other commercially available torque sensors, the CSHA2FL-CR15 yields a similar resolution of 0.04 percent of the torque sensor FSO of 50Nm. For example, Figure 4.4 shows torque ripple peaks of approximately 0.5Nm which are easily measured by the capacitive sensor.
5.2 Optical Encoder

The Broadcom AEDR-8710 proved a challenging solution for a robotic torque sensing application. The theoretical resolution of 0.16Nm with Torque Plate 2 was never realized and as shown in Figure 4.7 a resolution of 2Nm was achieved. While comparing this sensor to it’s industrial torque sensing counterparts it significantly under performs as 2Nm is 4 percent of the torque sensor FSO of 50Nm, which is over 400 times larger than the benchmark ATI Omega85 SI-1900-80 torque sensor. As this optical encoder was in a prototype environment it made for very cumbersome integration and maintenance. A custom bracket and mating components had to be designed and fabricated to mount the sensor and reflective artwork. The AEDR-8710 requires very tight tolerances between encoder and reflective artwork, which became a challenge in this prototype workbench. This sensor outputs a 5V single ended quadrature which is readily received by a high speed counter card, however is very susceptible to electromagnetic interference. If the encoder were to output a differential quadrature, as opposed to single ended, it could have utilized the benefits offered by twisted pair, shielded cabling to reduce undesired noise on the output lines.


[18] I. S. University, “Welcome to magnetostrictive transducers, actuators, and sensors at iowa state university.”


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[48] *Cup Type Component Sets and Housed Units CSDSHD Units*, Harmonic Drive.