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Survey of Force/Torque Sensor for Industrial Robotic Arm

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Abstract

With current industries leaning and moving towards Industry 4.0 and a steady rise in use of robotic arms with projected growth of 13.8% by 2024, it is sufficient to say, the use of sensors is also on the rise. Sensors that give vision and most importantly the sense of touch can greatly improve the rate at which a task is performed. This paper will introduce six-axis Force/Torque sensor and how it performs. This paper will also provide three main advantages of using force/torque sensors and its downsides when being used in real world. Finally, a list of force/torque sensor manufacturers are provided.
Keywords— Force/Torque sensor, Industry 4.0, FT sensor, Six-axis Force/Torque sensor, Robotic arm sensor

1. Current use of robotic arms

The first industrial robotic arm was invented in 1961 by Unimate, which subsequently evolved into the PUMA arm. Back then the robotic arm appeared and performed very simple tasks. However, today robotic arms have come a long way and have outperformed the PUMA arm by a great margin. In current times, robotic arms are used to increase the productivity and quality. Few common applications are welding, material handling, machine tending, painting, picking-packing-and-palletizing, assembly, griding, deburring, polishing etc. These tasks are very labor intensive and are thus assumed to be the reason for handing them over to robotic arms. The most important reason for picking robotic arms over humans is its ability to perform the task with great accuracy and repeatability. Furthermore, with improvements in the mechanical features and capabilities of a robotic arm, even in the medical industry has started investing in the world of automation. In 1985, for the first time, a robotic arm assisted doctors in a neurosurgical biopsy [2], this was a big achievement and a step closer to fully robotic surgeries.

2. Sensors used alongside robotic arms

Sensors of robotic arms are similar to the five basic senses for humans. Our sense of smell, taste, touch, sight, and hearing are used extensively throughout our daily life. Remove any one sense from a person’s life, and almost every task is affected. Take for instance the sense of smell. Removing the sense of smell will make an enjoyable experience of eating to a mundane task for stomach satisfaction.

In the same sense, when a robotic arm is equipped with sensors, the arm can detect/communicate with its physical surroundings with input signals from sensors. Some of the widely used sensors are listed below [3]:

Table 1: widely used sensors for robotic arm

Type of sensor	Subcategory and use
Resistive Sensor	Thermistor sensor, LDR sensor, piezoelectric sensor, and magnetic field sensor
Capacitive Sensor	For displacement and force measurement
Inductive and magnetic Sensor	Used for linear and angular displacement measuring and detect metal surface
Optical Sensor	Can be used as camera, velocity calculation, angle measurement, and object tracking
Piezoelectric Sensor	For measuring linear loads, and direction of sensitivity
Acoustic Sensor	Widely known ultrasonic sensor for navigation, distance between objects, etc.

There are various types of sensors alongside robotic arm. Each of the mentioned sensor plays vital role with one or more being more than the other if a task calls for it.

3. Industry 4.0

Before moving forward, here is an introduction to Industry 4.0. What is Industry 4.0? It is the fourth ongoing industry revolution which focuses on automation of traditional manufacturing and industrial practices, using smart modern technologies. A brief explanation of previous revolutions: Industry 1.0 introduced mechanization and steam powered engines. Industry 2.0 introduced mass production assembly lines, one for the first few being Ford's car manufacturing assembly line. Then came Industry 3.0, which gave rise to computers, and robotic arms. And the current Industry revolution is Industry 4.0 which we are entering and experiencing as of year 2020.

A smart Industry 4.0 factory consists of 4 layers, namely physical resource layer, industrial network layer, cloud layer, and supervisory control terminal layer [4]. Where the physical layer can be robotic arms, conveyor belts, and all other machines and parts on the floor which can communicate with each other. The data from the physical layer is collected by the network layer and stores in the cloud storage. This data then interacts with humans through the supervisory control terminal layer. With such a large network, machines can analyse and diagnose issues without the need of human intervention. This revolution has also given a rise to COBOTS = Collaborative robots that work alongside humans.

For companies to adapt Industry 4.0, there is a huge demand in force/torque (FT) sensors as it helps connect the robotic arm with other devices around itself and this helps to create a smart environment where every machine is able to communicate with each other. With growing demand, there is also growth in research and competition among manufacturer to produce more affordable FT sensors.

4. What is a Force/Torque SENSOR?

A force/torque (FT) sensor is a device that is capable of sensing, recording, regulating force and torque exerted on the machine. The forces can be from any direction. This can be compared with our sense of touch, even a small bug landing on one's hand can be felt by a human. Similarly, a robotic arm equipped with a FT sensor can detect very small amount of force and can then adjust its performance if needed. For instance, if a robotic arm is tasked with inserting a pin in a fixture, with help of a FT sensor, the process can be performed with greater control and provide process verification. This not only improves the rate of output, but also lowers the strain on the parts and the equipment, thus increasing the durability of said equipment.

FT sensors are used in numerous applications. From working in tandem with human beings to performing long tedious tasks, which can range from driving-in hundreds of screws a day to lifting heavy automobile parts. Using robotic arms will surely increase productivity, however with help of a FT sensor the productivity is much greater and ensures longevity of equipment. On a safer note, FT sensors are also used as a safety net for humans. FT sensors can decrease accidents involved with robotic arms by detecting unpredicted forces and avoids the entire process. This not only prevents accidents between humans and machine, but also prevents damage to the machines or other equipment's around the arm.

5. Technologies Used in Force/Torque Sensor

Strain gauge or piezoelectric are widely used technologies to measure the force. A Strain gauge is a thin wire or foil arranged in a grid pattern bonded to a thin backing material. The strain gauge is then bonded to the surface. The force is applied on the surface, it experiences strain and so does the strain gauge. A good bonding between a strain gauge and the surface is required for best results. As the gauge experiences strain, its resistance either increases or decreases. This change in resistance is very small and difficult to measure. Therefore, a wheat stone bridge is used to amplify the output into millivolts which can then be easily measured.

The piezoelectric sensor is constructed using elastic crystals sandwiched between housing material. When force is applied on a piezoelectric sensor, there is voltage change which is the measured and recorded. Here the force applied is proportional to voltage change. Piezoelectric sensors are also capable of measuring wide range of forces. However, due to this huge range, the sensor is better suited for dynamic loading rather than static loading. Piezoelectric sensors have a wider range of errors compared to strain gauges.

Comparing both technologies, a strain gauge is clearly more preferred over a piezoelectric sensor for its accuracy and resolution. A strain gauge is also less susceptible to temperature change which can cause error in recording forces and is less volatile when it comes to measuring constant force for a longer period.

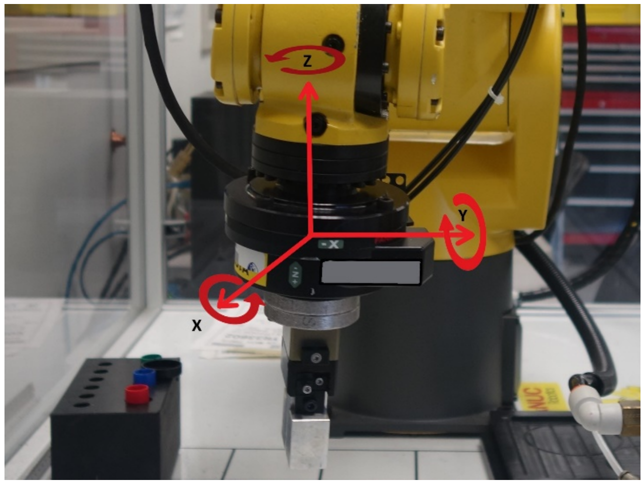

Fig. 1 Measurement of external forces and torque in six-axis using force/torque sensor

6. Types of Force/Torque sensor

The force torque sensor can be categorized in 3 different types:

i. Simple pressure/force sensor - This is the simplest of three. These are also known as mechanical pressure sensor and can detect forces, usually in a single specified direction. These are not ideal for sensitive pressure measuring task.

ii. Strain gauges force sensor - These are widely used in research for a robotics and can be found in two variants. As a load cell, used in weighing scale for measuring weight in single specified direction or multi-axis (3 axis) force sensor. It can measure forces in multiple directions.

iii. Multi-axis force/torque sensor - This can measure forces and torque in all 6-axis, which are, F_x, F_y, F_z, M_x, M_y, M_z, this can be seen in Figure 1.

7. Advantage of using force/Torque sensor

To better understand the benefits of force/torque sensor, its advantages needs to be discussed. Below are its three main advantages: using FT sensor as a proximity sensor, its ability to provide constant force and then maintain the said constant force, and a major advantage of FT sensor, its ability to provide user safety. However, it is important to know that these are not the major reason to have a FT sensor in a robotic arm, rather they are three of many other advantages that are taken into consideration when FT sensor is requested to be installed.

A. As a proximity sensor

A force/torque sensor can be used/functioned as a proximity sensor when attached at the end of the robotic arm, followed by user desired end-effector. If there is a FT sensor at the end of the robotic arm, when the arm touches an object or an surface, the FT sensor can detect the force and alert the user, or in most cases, stop any further mechanical movement of the arm. This can prevent accidents, damage to the robotic arm, and even avoid damage to the object/surface that is being handled.

A FT sensor can also be tasked for accurate inspection by using its proximity sensing ability. The arm can be programmed to move around a manufactured part and hit few specific points of the part at specified force. If the force response does not correlate with what is predetermined, the operator can be alerted to either discard or fix the part until it matches required specifications.

B. Constant steady output

With the help of a FT sensor, a constant production output can be achieved. This is best explained using an example. Take the task of Polishing or grinding for instance. Any repetitive polishing or grinding task on flat or – almost always- curved surface and benefit from a robotic arm. Examples take the process of grinding and polishing an automobile at a manufacturing plant. The automobile in question is made of steel and needs finishing before paint. With help of a robotic arm, the process can be speeded up. However, the surface of an automobile is not flat, and thus a varying a degree of force is required to grind or polish the surface. Over the limit, and the arm can scratch the surface, under the needed force, the arm is being inefficient.

Now, for the process above, if the arm is equipped with a FT sensor, the arm is getting real world response and can adjust its force needed to maintain constant pressure between the arm and surface. With a FT sensor, the task has now increased in speed, there is almost no possibility of scratching the surface or being inefficient. Every automobile in the manufacturing plant is getting its own personal touch.

C. Keeping safety in mind

With use of a FT sensor, the safety of its operator, the robotic arm, and its surrounding greatly increased. If a robotic arm is being operated and accidently hits a surface or a human, it has no way of knowing if the force its applying is unsafe without a FT sensor. In many cases, the arms are programmed to work automatically throughout the day, and if accidently, an object falls in its path, or a human enters its workspace, accidents are bound to occur.

Now, if a FT sensor is being used here, the arm can be programmed to stop all tasks if any unpredicted force is detected. This can greatly reduce accidents and maintain safe work environment.

8. Problems associated with Force/Torque sensor

There are countless benefits of using and integrating FT sensor in a process. there are downsides associated with the FT sensor too. Starting with the manufacturing process. A FT sensor needs to be highly accurate, and to achieve this accuracy, copious amounts of research are involved which can be expensive. Large facilities to manufacture a FT sensor can be expensive. Each component needs to be of the highest quality available to achieve an accuracy of ±0.01 percent of its full capability. At every step, the price of end product goes up, which is passed over to the customer and thus a FT sensor ends up prohibit cost, which many companies cannot afford.

A user related problem with FT sensors are to be aware of overloading. This is one of the most common problems associated with FT sensors. Overloading can damage the sensor and destroy its accuracy [5]. This can also lead to over working the robotic arm and damage the arm as well.

Furthermore, regular calibration is also required for a FT sensor. A proper calibration is necessary to ensure the force/torque being recorded and measured is accurate and reliable. A task that involves high accuracy, such as, using it for medical surgery, the FT sensor is required to be calibrated at ISO 17025 certified lab for testing and calibration. ISO 17025 is an international standard for testing and calibration laboratories, the standards and requirements are very high to maintain and operate such labs. Workers needed for the lab are also required to be highly skilled in the field of testing and calibration. The calibration step involves sending the sensor to one of the few labs in the country and it can take days or even weeks until the user receives the sensor back. Not only is the calibration process expensive and time consuming.

In recent years, manufacturers are marketing self-calibrating FT sensors and there are also many research papers that provides their own solution. These methods have error of 1% - 3% [] at best, which is nowhere close to ±0.01% error accuracy provided by certified labs. Self-calibration methods provided in various research do work to some extent but are limited to the type of task that can get away with expected error. At the end of the day, the smart choice would be to send the sensor to an ISO 17025 certified lab and have a backup FT sensor available.

9. Leading Force/Torque Sensor Manufacturers

In the last decade, a lot companies have started manufacturing FT sensors. Though some of the first few and the leading brands are listed below.

- ATI Industrial Automation, Inc. Based in Apex, NC. ATI has been producing Multi-Axis FT sensors and has been leading the market for decades. They manufacture FT sensor using silicon strain gauge for low-noise and high overload protection. Their main customer base are manufactures using robotic arms and for biomedical research.
- Robotiq, based in Quebec, Canada. A much newer manufacturer in the market that offers FT sensors for specific tasks and machines rather than a single design with varying load capacity. This means the FT sensor by Robotiq cannot be interchanged with another machine performing different task, though this is rarely done. Their products vary from gripper-based FT sensor, to a vacuum FT sensor for pick and place task.
- Fanuc, based in Oshino, Japan, a leading robotic arm supplier over the globe. Fanuc provides their own line of multi-axis FT sensors. They could be fitted onto other brands of robotic arm with crude fitting but would also not provide accurate results. Their FT sensors are considered robust and are widely used for manufacturing processes such as polishing, grinding, deburring, mechanical assembly, accurate inspection and so on.
- ABB, based in Zurich, Switzerland. ABB is another leading robotic arm manufacturer which provides its own line force/torque sensor solution. They offer up-to 70% in time saving when FT sensor is integrated in their robotic arm.
- KUKA, based in Augsburg, Germany. KUKA is yet another leading robotic arm manufacturer that sells its own line of product and few newer models comes fitted with FT sensor.

10. Current Applications of FT Sensor

FT sensors are widely used in current industries, hospitals, education sectors and many other places that operate robotic arms. However, most of them being very expensive, they are not implemented everywhere. The following are some of the most widely used places where FT sensor is either required or is implemented.

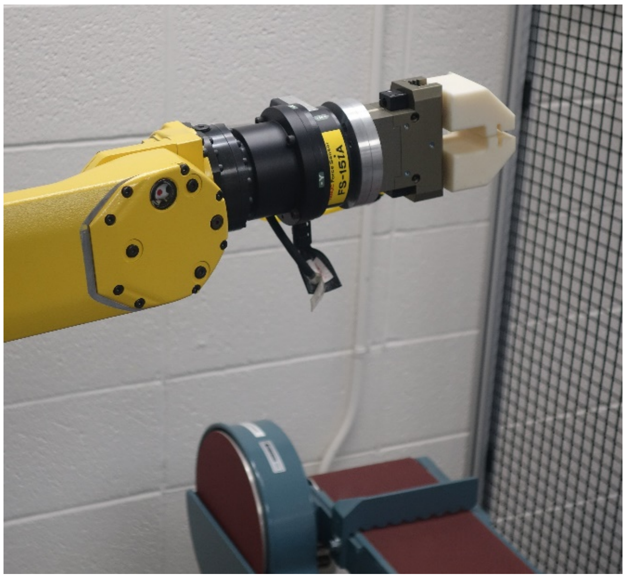

Fig. 2 Robotic arm equipped with six-axis force/torque sensor for grinding and polishing in a work cell

Applications of Force Torque sensors:

- Mechanical Assembly – Widely used in automobile industries for assembling precision parts.
- Polishing, Grinding, and deburring – Also, widely used in automobile industries. Any task that required constant force, seen in Figure 2 below.

- F/T feedback **–** Used in nuclear environment.
- Physical rehabilitation – this is currently in research stage is being used to produce prosthetics.
- Product testing – Almost any manufacturing plant that needs repeatability testing.
- Medical **–** Robotic arms are being used for complex precision surgery.

As mentioned above, polishing, grinding, and deburring is an ideal application for robotic arms fitted with FT sensors. But a greater emphasis is needed to be given here, as these tasks are where FT sensor is currently used the most. For grinding and deburring, a FT sensor helps perform the task preciously by compensating for the small deviations caused in the casting process and ensures the head of the robotic arm is always aligned with the part and is on track. Often, a casted part is not formed the way the user wants it to be like, these flaws are also very minute, but needs to be dealt with. With the help of a FT sensor, the arm can detect these flaws and deal with them accordingly by applying required force to grind or deburr the part.

And for polishing, the same method is used to ensure the best results. An FT sensor can detect change in surface shape and tells the robotic arm to apply required pressure to maintain constant force between the arm and the part. Similar to grinding and deburring, the pressure applied by the robotic arm and path are changed in real time for optimum results.

With the aid of FT sensor, robotic arm applications have expanded and are being accepted by various industries wide range of application to create a complete smart system where each and every machines are connected to a central network and are able to work in unison.

11. Beyond Robotic Arm

There is a growing market for FT sensor's use beyond robotic arms. These demands are currently in research/developmental stage. Though, the most promising use of FT sensor is in the field of prosthetic research. Like a robotic arm, a prosthetic limb with the help of FT sensor can send feedback either using the methods of neurons or haptic motors. This has been tested and can soon be seen in market for people with disabilities. Obviously, FT sensor in a prosthetic arm can be nowhere near the sense of touch or the ability to feel the force. However, with rigorous research, we can certainly get there in future.

12. Conclusion

In this paper force/torque sensors are is introduced and its advantages are laid out for a researcher or manufacturer wanting to integrate FT sensor in their field of work. Its advantages and problems associated with FT sensor are also provided to cover every aspect of its serviceability and integration associated with robotic arms. Finally, current leading manufactures and the current applicational world is discussed in depth. With all this provided information, a consumer can easily decide if their work can benefit from FT sensor or not.

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