Analysis of Industry 4.0 applications in automotive industry

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ABSTRACT

Industry 4.0 is a very concept which has some very important features. As industrial revolutions happened before in history, Industry 4.0 can be realized through many high technologies. Through large number and high accuracy sensors and transducers, cyber physical system can generate a virtual world corresponding to the real machine, factories, so we can realize monitor and control through computer. Not only the machines, the materials and components can also be connect to the virtual world through internet of things through some specific coding such as 2D code and with specific detection machine. In this way we can realize a smart manufacturing where the ERP and MES are connected together to exchange information. On the production line, variable productions can be produced with all mentioned technology and the trace of problem or defects can be realized. Under this background, a bolt/nut machined is designed to realize operation with three dimensions of nuts in Industry 4.0. It is worked under a basic condition that the nut at work point should show a specific direction which matches the part on the pushing head which in charge of rotate the nut. So a specific nut feeding system is designed to using sliding to transport nut from one position to another, while during which the direction of nut will not change, so the nut can be transported to the desired position with desired direction. Since during working the pushing head will rotate so in order to keep it as the pre defined position while it contact the nut, some specific end-stop is designed using two conjugate surfaces, and with the downward without rotation at first part the desired position is guaranteed. Types of physical quantities are evaluated to give information of the working condition, the pressure between nut and pushing head and the torque between nut and pushing head are very important, with proper sensors or transducers they can be measured, and based on the torque curve or pressure curved, it can realize the control and diagnostic. The control of propulsion is based on two things. The first is the speed of rotation and translation should be same in torque control, and should be sometimes same and some times changed under pressure control curved. As the torque and pressure change, some contact points can be found, can relative control strategy is implemented. Also by compare to the normal working condition curve, diagnostic process can be done, some abnormal results are defined and relative reason are specified and also the related correct action is defined. Also some other quantities such as flow rate of products can be calculated from the sensed quantities. Finally, some exercises are carried out using MECT starter kit and related software QT creator and MECTcontrol to see if it possible to using this device realize control under Industry 4.0.

Key words: Industry 4.0, cyber physical system, internet of things, bolt/nut tightening, strain gauge, torque transducer, MECT starter kit

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Section 1:Background

Industry 4.0 is a very new concept which is firstly came up with around 2011 by German government. It originates from some very high technical projects which performed or going to be performed by German government, the key point is to enhance the use of computer during traditional manufacturing process. And of course this enhance of computer mainly refer to the increment of degree of computerization, this means not only to simply introduce computer and some other related technology into process of manufacturing, actually this target has already achieved by many factory with highly automatic equipment, we should keep on the using of computer together with information and communication technology to change the whole manufacturing process in variety aspects. Actually industry 4.0 is just like the other ‘hot words’ such as AI, block chain, self-steering and so on, all these words are very popular recently because of the improvement we got in technology, the great attention paid by government and also the broadcasting by the mass media. It seems everyone who cares about the technology know the words industry 4.0 but on the other hand, it can be said that almost no one know the meaning behind. This is not a bad phenomenon as we firstly think, on the contrary, it shows infinity possibilities. Up to now Industry 4.0 has been put many meanings which relate to all the aspects, it should say that all these meanings are true, because Industry 4.0 is still a concept keep growing, and also the concept itself is a numerous one since it consider the whole industry.

So general speaking, Industry 4.0 refer to every future imagination or reasonable speculation on the whole industry based on two type of technologies.

The first type is the technology which is already improve to a certain mature level, such as some computer science and manufacturing process such turning machine, conveyor belt. This type of technology is what we already used in manufacturing system nowadays and is still going to be used in the future.

The second type of technology is the key points, the new technology. Some of these have just started to improve and some are still remained in concept. Some preventive examples are AI technologies which help to machine learning and results in no human intervene needed.

1.1 Industry 1.0 to Industry 4.0

It is obvious that the number 4.0 in Industry 4.0 present the big generation of industry and the 0 behind the decimal point is the small level inside the generation. Actually now 2018 I consider we still in the Industry 3.X which this X present that we develop a lot inside the Industry 3.0 but we still have a certain distance to Industry 4.0, the main symbol which shows we move from on industry generation to another is technology.

Throughout human history, there was three industrial revolutions and we can say that now, we are in or about to be in the forth industrial revolutions. Every industrial revolution lead human to a generation of industry from 1.0 to 4.0.

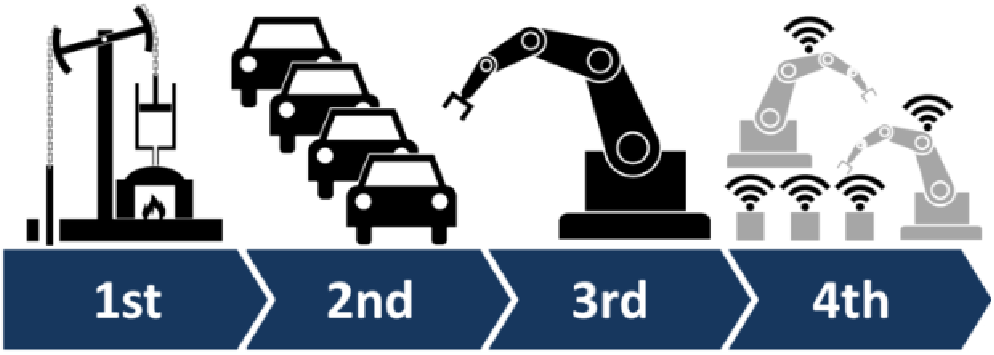

Figure 1. The four generation of industry

As shown on the picture above, up to now and recent future we have four generation of industry which have its symbols. The industry 1.0 has the internal combustion engine and mechanical transmission while the industry 2.0 shows its ability to do mass production. For industry 3.0 the use of PLC (programmable logic controller) is able to control actuators such as robot arms so we realize the automation. And finally, the industry 4.0 is shown as robot arms plus some symbols of WIFI, this implies that industry 4.0 is the extension of industry 3.0 whose core is automation, and beside automation, there is a very strong connection between different machines.

Figure 2. The steam locomotive

It is apparent that the start of every lip from Industry N to Industry N+1 is exclusively depend on the technology. Before first industrial revolution, people do every thing by hand with very low efficiency. But in late 18 centuries to 19th, many intelligent inventor gives their master works which extremely propel the development of industry. George Stephenson, the father of railways, realize the first stream locomotive which is able to carry passengers. And also the James Watt, he is one of the most important person during first industrial revolution. He got many impressive achievement and the most important one is to improve the Newcomen’s steam engine to his Watt steam engine which is fundamental of first industrial revolution. In order to keep in mind his achievement and make him an best example, the unit of power W is given after his name. Also, there was numerous pioneers contribute their life and great thoughts during that specific time, the technology is improve rapidly and the world is step into Industry 1.0 which people realize to replace the human by mechanical machines propelled by steam engine, this extraordinary increasing the efficiency lead to huge development not only on industry but also on the whole human society.

In late 19^{th} and early 20^{th}, people continue to step into Industry 2.0 around the electricity. In these period, the technology shows its strong power to influence the industry, a lot of manufacturing method is improved a lot by installation of new technology. The most important aspect of Industry 2.0 is the appear of mass production. And this mass production is firstly developed in American cause it have huge advantages in row materials, capital from all over the world and the too much less expensive manpower. There are two ways to realize the mass production. The firstly one is to produce some standard component such as simple components screws and springs. In this way, we can simplify the manufacturing process into assemble process which take less time and cost much more less, also the efficiency in increasing cause every single component is able to be mount in any product, this convenient exchange accelerate a lot the speed. And another way is to design a production line, split the whole work into pieces of small work. As a consequence the workers don’t need to remember to different total process and can focus on a specific work and repeat it. Henry Ford is the first person to manufacturing vehicles with production line and this action benefit him and also the whole world a lot.

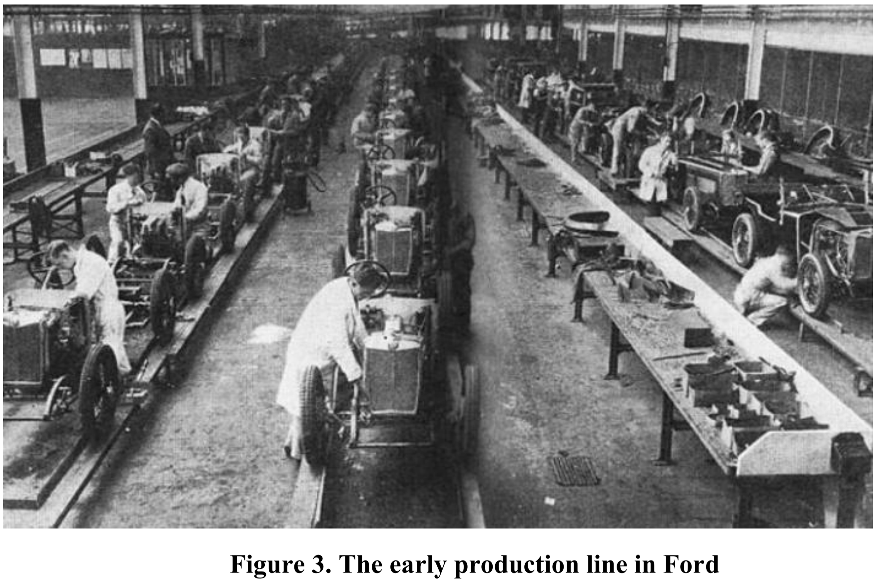

Figure 3. The early production line in Ford

Then after the world war second, electricity has been very common in industry to be used, not only for the power supply, but also for its ability to transfer information. With the development of computer and information technology we are able to bring computer into manufacturing process. We can solve many problems in numerical, and the word 'numerical' became the hot word through the whole Industry 3.0. Many calculation can be done numerically by computer and so does the control. People don't need to stand in front of the operation machine and see how it going. With sensors and computers, it will automatically do some decisions, this is a huge improvement, since all decisions made by human is to some degree subjective, and this subjectivity will results in different decision when face the same problems. So the meaning is automatic by computer is always more reasonable, more efficiency, more consistent among very large number of cases. As a result, every machine is develop with its numerical version. But also automatic is not the god, it still have some drawbacks. The most important, the cost, the cost is not affordable for some mid-small size factory while it is very good for companies with a large number of production. And also, since those numerical machines cant be as smart as humans, they can only take some small, simple, repeatable decisions, it cant handle emergencies such as failures or any other conditions which the programmer didn't consider before. As a result, human is still necessary during the manufacturing process, but not as a operator as before, but as a supervisor who is capable of solve unpredictable problems. This acquires more knowledge and ability for the workers.

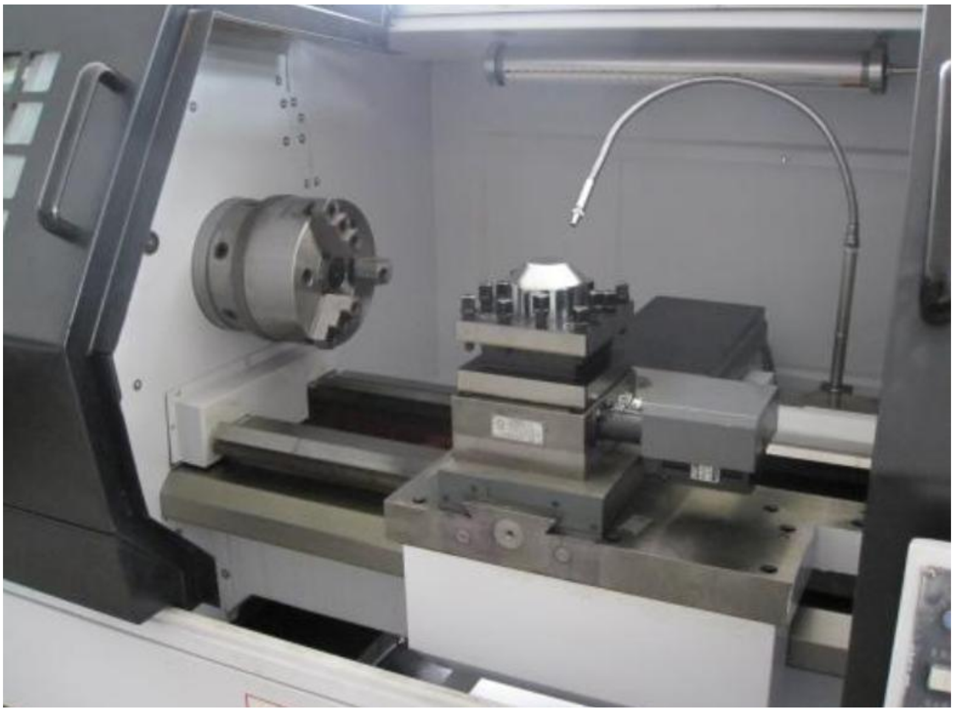

Figure 4. Numerical turning machine

In figure 4. it shows a numerical turning machine which is very common in nowadays manufacturing process. With pre-defined code the machine is able to turning specific material into a specific shape. Every code is consistent to a whole turning process. No matter change the row material or change the target shape, the code need to be re-program. So the machine is still an specific machine but able to avoid the dimension tolerance caused by human effect, and with all the operations done by non-human power source, it can reach a lower operate time for each component.

And finally we are reaching or about to reaching the fourth industrial revolution which will lead us to industry 4.0. As the three industrial revolutions before, the pushing force is always the development of technology. Not only improvement of the automatic technology, but also others such as computer technology and informatics and communication technology. All this result in a key word, intelligent, or smart. As mentioned above, for a numerical turning machine, we can operate it to only a specific condition, but in the world intelligent, the machine behaviors like human, which means we don't need to change the settings and the codes every time, but the machine or the system can do it automatically and autonomously.

1.2 What is Industry 4.0

Industry 4.0 describe the future of manufacturing process, or not only the manufacturing process, but also includes the upstream and downstream of the it. It describe an intelligent system thanks to the development of AI, this system is in charge of manufacturing and management of transportations of material and final products inside same company or between different companies such as suppliers and OEMs.

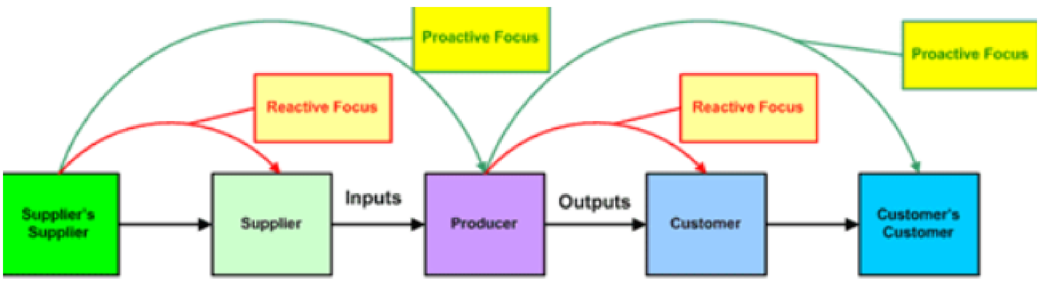

Figure 5. The value chain

Every company is linked to others through the value chain which present the add of value of a product, it includes the supplier of every row material and every intermediate manufacturing and machining and also the seller and dealer. If the producer use the intelligent system mentioned above, it can also have data exchange with other companies use same type of system, the two intelligent system come from these two companies share the same information will make some win-win decisions again automatically and autonomously which might hard to be revealed before.

This intelligent, smart system with all the small part which also have some smart attributes, can operate the whole process of the industry automatically and autonomously. Automatically is the extend of Industry 3.0, means it don't need human to operate but can do the pre-decided operation by itself. And the other word autonomously means that it can solve the problem by itself with the machines under this system. So its not like only a computer to solve all the questions, but all the small machine inside this system is capable to solve problem relate to it, which shows a very high stability.

In Industry 4.0 we would have many possibilities and much less limitations but it still need time to achieve that..

1.3 Cyber physical system

Cyber physical system is a core of Industry 4.0, since Industry 4.0 is tend to control everything without human intervene, the most important thing is to present the real world into sort of information which can be understand by the computer. The job is doe with the help of cyber physical system.

Figure 6. Cyber physical system

The picture shows the three key words relate to cyber physical system, computation, communication and control shorten as 3C technology. Cyber physical system is a very complex multi dimensional system which integrate the computation, the internet and the physical environment. In order to present the physical world in internet world, the most important thing is the sensors and transducers, so the cyber physical system requires highly accurate, reliable and stable sensors and transducers, it will convert all the physical quantities which the users might use into electrical signals, and then after proper coding, these electrical signals will transform into digital signals which can be read and understand by computers. Also, since the information and data generate by the physical world is huge, the system require a large computation ability. Once we have convert the useful physical information into digital signals, we can say build the same thing in the world of internet, with proper actuator, its able to control and modify what really happen in physical world in a remote way, and also real-time.

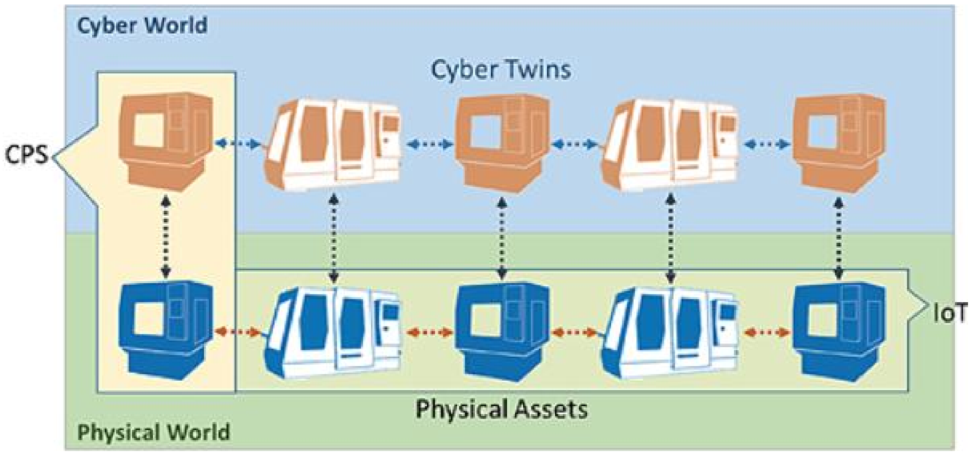

Figure 7. Cyber world and physical world

Figure 7 shows the two world, cyber world and physical world, the cyber world is formed on the base of physical world, and we can use it to control the physical world remotely.

The target is far away from been realized, we are still on the way to build a cyber physical system which is capable of sensing a very large operation machine or system, it need the development of big data technology to deal with the enormous number of information.

Also the requirements on sensors and transducers are strict which means the cost will be very high. And the also the speed of data exchange need to be quick, because any delay of this system means the miss of timing to control the real machine which may results in very sever accidents.

1.4 Internet of things

The name 'Internet of things' consist two meanings. The first meaning is that it is strictly relate to the internet, and so we can treat it as the extension of internet which means it connect something and transfer data in between them. And since it is more advanced than internet, it will not only connect the limited type of devices such as computers, the telephones. The second meaning is relate to the word things, it means the user end will not limit to the computers, but to every thing, a desk, a steel panel, everything you need can be connect to this net and realize data transfer with others.

Figure 8. Internet of things

Sure everything can be connected to this big net, but not as simply as the computer with cable or the phone with WIFI. It do need some different technology. RFID the shorten of radio frequency identification uses electromagnetic field to recognize some specific tags and read the information inside the tag. So for something we want to connect it to the net, firstly we conclude the useful information of this thing, where it go, the mass, the desired color and so on, convert these information into a specific tag which can be recognize by RFID, in this way we can use the useful information related to this one on the machines also connect to the internet of things which physically distanced. Also there are other technology based on 2D code, infrared ray sensor, GPS, laser scan, the method are similar, we generate a specific symbol or tag which contain information and put in on the related things. With proper protocol, we can realize the communication and data exchange between anything, and we can track, management and monitor everything we want.

It can be seen that internet of things is very important and useful in cyber physical systems, it help to connect not only the machines in operation, but also the material and the final product into the cyber world which facilitate the management of the whole manufacturing process.

1.5 MES and ERP

MES stands for the mechanical execution system and is the system controls the manufacturing process and used by the manufacturing department, it monitor and management every step to produce the products.

ERP is enterprise resource program, it is used by the business department and is more like management information. For example, the ERP system is dealing with the information from the orders, how many products need, when should be finished, what is the specific requirements.

And in traditional company, these two system is isolated, which means they hardly change information. The MES know that some machine is broken, some material is not qualified, but ERP don't know. On the other hand, the ERP knows the change of orders but MES don't know. This make a gap between these two systems.

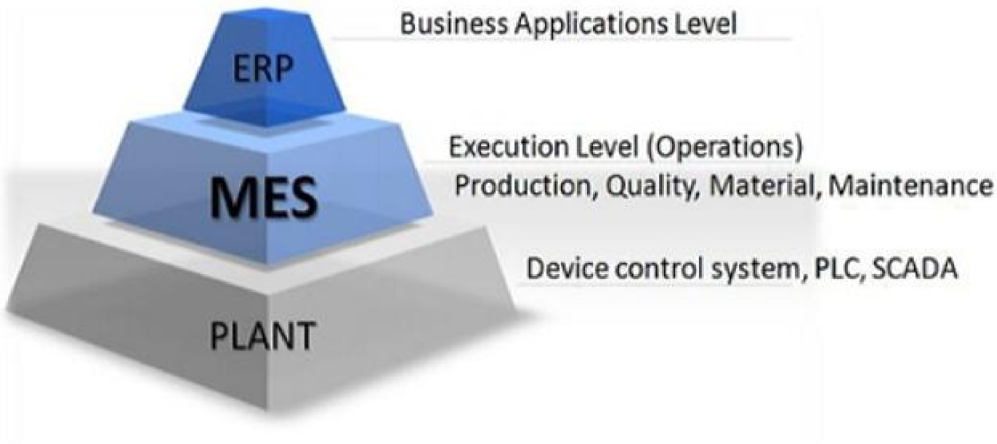

Figure 9. MES and ERP

As shown in figure 9. MES and ERP are separately and result in the lack of information sharing. In Industry 4.0 and also in now late Industry 3.0, the trend is to break the wall between MES and ERP, to make them a same system. With this united system, the production line can receive more quick and accurate the information directly to the customers.

1.6 What can we do with Industry 4.0

With all the requirement above, it comes to what we can do in a Industry 4.0 manufacturing system. First it is possible to realize rapid, small number ,specific production. Which means on the product level customers will have many choices and can choose product differ from the others. Of cause it will increase the cost but with system in Industry we don't need to change tools, materials and re-program, re-setting. All the changes can be done by the system automatically and autonomously. We only need to define the specifications relate to every product. With internet of things, we can mark the material used to produce version 1 differently from version 2, so when different material passing through the production line, they can be treated under different operations in order to make them into their own desires. This is the smart manufacturing.

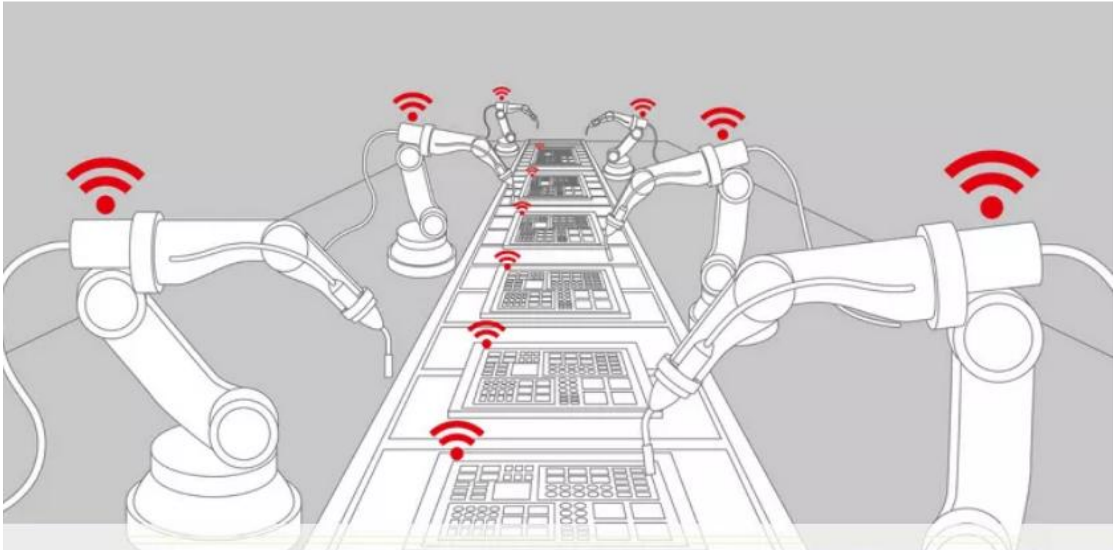

Figure 10. Smart manufacturing

Smart manufacturing as shown in figure 10. The robot arm can be used in manufacturing different products, the only need is to recognize the tag on material and get the information to decide the correspond operations

Also, with the application of all these sensors and big data technology, it is possible to collect information during the using. Take vehicle as example, it is possible to measure the engine profile, the adjusted seat, the frequency of some function used, with the sensors mounted on vehicle. We don't even need to put dedicated sensors since vehicle itself contain many sensors, the only thing need to do is to connect the vehicle product into internet of things. So with all those data generated during its usage, it is possible to improvement the version or help to design the new prototype. And also, the condition of the vehicle can be inferred which help to prevent accidents.

Another big advantage is to share information with suppliers and downstream companies, also with companies of same level. If we have data collected from every level of produce process and also the transportation process before and after the manufacturing, the supply chain is definitely more controllable. We can adjust the production among factories or even among companies since the information is exchanged through internet and also the production line is not dedicated as before.

Last but not least, with cyber physical system, the diagnose and maintenance can be easier. In a traditional manufacturing industry, if something go wrong, it usually not so easy to trace the source, but in Industry 4.0, every machine is connect to the net and generate it's own data relate to the operation condition, so it's very easy for all those machine to diagnose themselves autonomously on the base of data generate. And also if something go wrong, it is convenient to trace the part where the abnormal data generated.

1.7 Some limitation need to be careful

Figure 11. The internet safety

Since in Industry 4.0 all the things is relate to a internet, it is extremely important the safety of the internet. If the internet is hacked, the whole industry will be under attack, so it is necessary to define a strategy where some parts can be removed or disconnect to the whole internet of things while they are under attack.

Also there will be problem of privacy and patent if more than one companies are connect to the same internet of things.

Industry 4.0 is the determined future, but it still needs lots of effort to achieve it and to widely spread it into all industries. Up to now there is still some limitations. The big data technology limit the size and speed of the whole system, so the application is limited now, not only the size but also the level of complication. How to save and manage data of this number, how to select the data wanted from the sea of data and how to deal with them to draw information is still the key point. Although the computer system equipped with AI or machine learning ability can learn to control the manufacturing process even without human intervene, the technology is still far from fully replace the human. And also there remains many protocols and standards not been defined, the big direction is not a problem, the details are the next targets.

Section 2:Bolt-nut tightening machine

Although in Industry 4.0 we will mainly see the robots or some very all-round machines, it is still very meaningful to investigate some single target machines. It will not only help to accelerate the automation level, but also will help to quickly step into the world Industry 4.0.

In order to do this, I roughly design a machine used to tighten the bolt/nut structure. The idea is to design a machine that is capable of operate with more than one dimension of bolt/nut, and is able to operate with a relative wide range of dimensions of bolt/nut if change only very few parts. And it is possible to work even with different working angle, which means that the direction of bolt is not limit to the vertical one, working with different angle can be realize by modification of the propulsion system. And this machine is able to be a end effecter to be mount on the end of a robot arm. Above all, it shows many advantages which help the automation and the smart manufacturing.

This machine is designed to be able to operate with three different dimension bolt/nut with hexagon head screws. The choose of this type of machine is because the combination bolt/nut is very common in automotive industry, especially in the cylinder head and cylinder block, usually they have some specific usage with sealing and force balance, so it will require more during the tightening process. And also, this machine can be applied to other fastening type such as with single screw, just need to do some little change, the main design idea and process are the same.

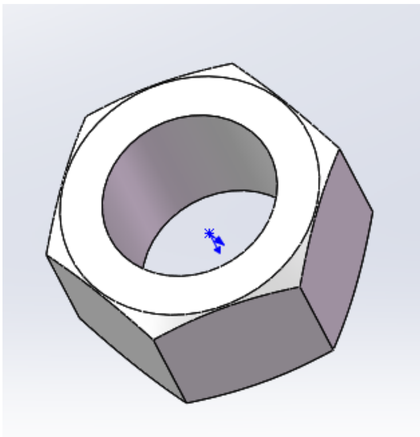

Figure 12. The 2D vision of nut

So this machine is designed that in order to tightening a bolt/nut up to a certain value of preload, on one hand it is very timing consuming and energy consuming event for a human with simple tools, and even with some electric drill type hand tool, the repeating work could be a waste to use human power. On the other hand, for the applications relate to engine, commonly the requirement of preload is of certain level of severity which will be hard to achieve by hand precisely. So the automation machine is the most suitable to do this kind of repeating works with satisfied precision. And since for an automotive application in Industry 4.0, it should have some properties to be applied in smart manufacturing. This can be achieved by the ability to work with different size or type of screws. In this case, 3 different size but same type bolt/nut are selected, and the dimensions in real application can be chosen as the 3 most used one.

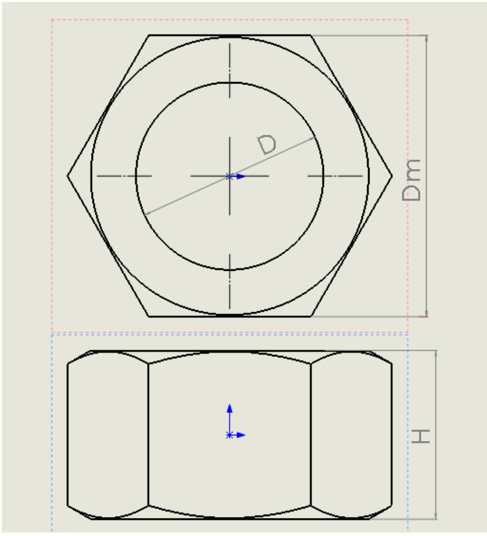

Figure 13. The 2D vision of nut

The 3 dimensions of the bolt/nut are selected as M12,M16 and M20, and it can vary depend on applications, but the whole method is the same. The nut is the common hexagon shape and the three main dimensions is shown above, the screw maximum diameter, the height and the diameter of the inscribed circle which is also known as the width across the flats. The dimensions are according to the type of hexagon nut ISO 4032, and some more datum about the related bolts can also be find, including the total length, the height of head, the nominal length range and the length of the thread. Together with the work pieces dimensions, the proper length of the bolts can be chosen. The in our case, the dimensions according to M12 bolt is found and 3D model is build to investigate the working process. The main detailed datum about nut are listed below.

ISO 4032	Pitch	Thread D(mm)	Dm(mm)	H(mm)
M12	Fine pitch	12	18	10.8
M16	Fine pitch	16	24	14.8
M20	Fine pitch	20	30	18

Table 1. Dimensions of nuts

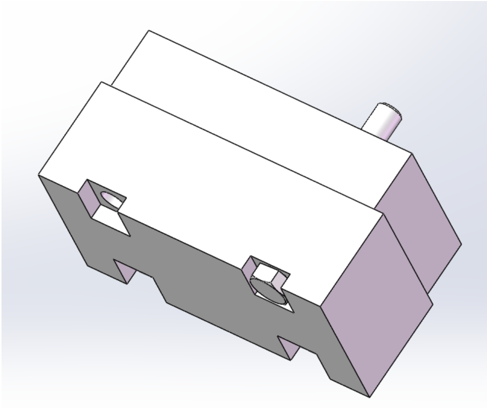

Figure 14. The working condition

And the working condition is assumed to simple clamp two rectangle pieces together. And the parts of system in charge of movement of the bolts stem such as feed of bolt and put it through two holes in upper and lower work pieces is not include in the design, so to simplified the situation, the bolt is put in the slot of the lower work piece, and the bottom surface of the bolt is at same plane of the bottom of lower work piece. In real application, the bolt can be appear in different direction and relative position so it will influence the design of the working plane, the working plane is not necessary to be a large flat surface, but maybe need some holes and slots for the space of bolt head.

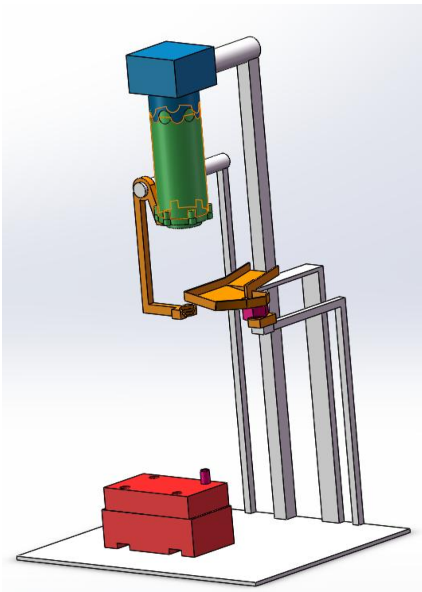

Figure 15. The nut tightening machine

The design is shown in figure 15. And as shown above, the system of the machine is divide into some parts which are indicated in different color. The white color part is the frame, the two red components in the bottom of the picture are the assumed work piece. There are two pink parts, the bottom one is the bolt and the middle one is the nut, their type and dimensions are predefined as a hypothesis working condition requirement. The yellow parts composed the nut feeding subsystem, the aim is to transport the nut under the middle of the green part which are the working part in charge of tightening. And on the top is a blue part as a symbol of the propulsion system. Later In this section, I will make more detailed introduction of each parts, the design strategies, the dimensions and the working principles.

2.1 The frame

As shown is figure 15. The frame is mainly in the bottom and in between the colorful parts. It is a big frame made of metal with many extrusions which helps to connect and sustain different parts in the air. And also it helps to insure the relative position which is very important during the operation. Besides those connecting column, in the bottom there is a big panel, this panel is to provide a horizontal working plane.

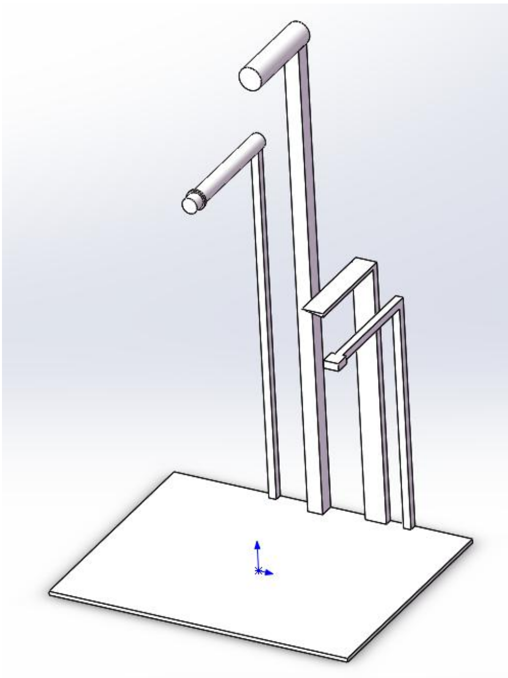

Figure 16. The frame

And there are four extrusions up to about half meter. From left to the right, the first one is connect to the nut feeding end, the nut feeding end is amount to the extrusion through a hole and it will meet the annular structure, so the position is guarantee. The second one is connect the propulsion system much higher, it should be more rods in order to hold the whole propulsion above but since in my design I didn't go in too much in the propulsion system, I reduce the number of rods to one to connect the symbol of propulsion system. The third is to sustain the nut feeding channel and the forth rod is mean to have a end stroke of the nut pusher. Since I didn't pay too much attention to the design of frame, some verifications are still need to be carried out since on the top, those horizontal rods in working under certain shear stress.

But since the parts to be sustained by the frame are not of high mass, and there won't be too much vibration and relative movement between those parts, I think the frame is in both dynamic and static stable with the select dimensions. The second problem is the shape and dimensions can be modified to obtain a better man-machine relationship and also the space occupied can be reduce if some modification can be done.

2.2 the propulsion system

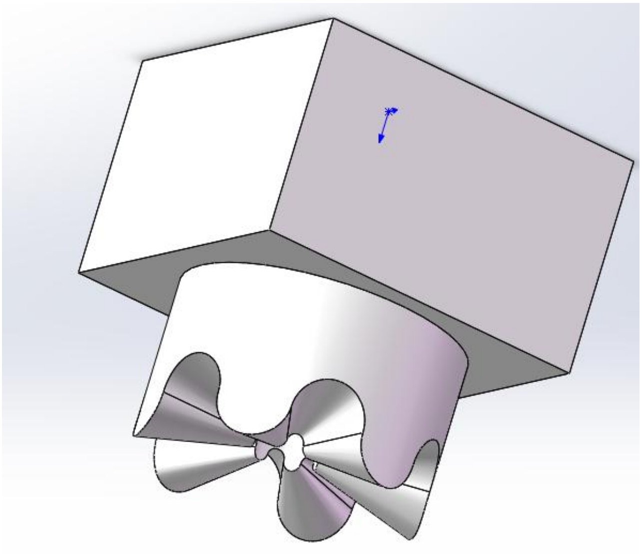

Figure 17. The propulsion system

The propulsion system is the system in charge of the moving of the whole system. It include the system move the nut feeder, move the tightening head and the nut guider core, and also the turning of the tightening head. All there movements can be divided into two groups, the translation and the rotation. In my design, I didn't specific the way of propulsion, and the figure 14 is only the symbolic present the propulsion system, the important point I want to express with figure 14 is the cylinder structure below which will do some help and I will explain later.

But actually the machine doesn't need some peculiar propulsion system, the normal one can definitely be suitable. For the translation, it can be realized by a solenoid, with control of direction of current, the reverse movement is guaranteed, and with control of amplitude of current, the moving speed is under control. Another way is to use the fluid, in pneumatic way or in hydraulic way. The pressurized gas or fluid push the piston, and the piston connect to the moving parts, the speed control is accompanied by the control of flow rate, and the pushing force can be adjusted by the pressure. And both for translation movement or the rotating movement, the electric motor can in charge. The rule for the select is based on many aspects. If the system is light, then it is easy to hold it on the air safely, otherwise, additional structure need to be implement in order to keep the whole system away from ground. And the cost is another issue, if the propulsion is expensive, it may be better to use some technology advanced machine instead of this one. Also, different propulsion system will strongly influence the control strategy, since there are many variables to control, the speed, the force, the displacement, different propulsion system will influence the variables need to be measure and so the related design of the space for install the sensors. Anyway, there are many possibilities in propulsion system, and hopefully in later there will even more and more suitable ones

2.3 The pushing head

The pushing head is belong to the green part in charging of nut tightening, and it is the bottom part of the green components before. The pushing head is directed connect to the nut, and transfer the translation and rotation movement. So it should be made of some metal material which is able of sustain high stress and little displacement. Exceed displacement will cause the contact with nut not suitable and far from the design which may cause the tightening fail or even damage the machine. On the other side, the pushing head is connect to a stem and finally to the propulsion system.

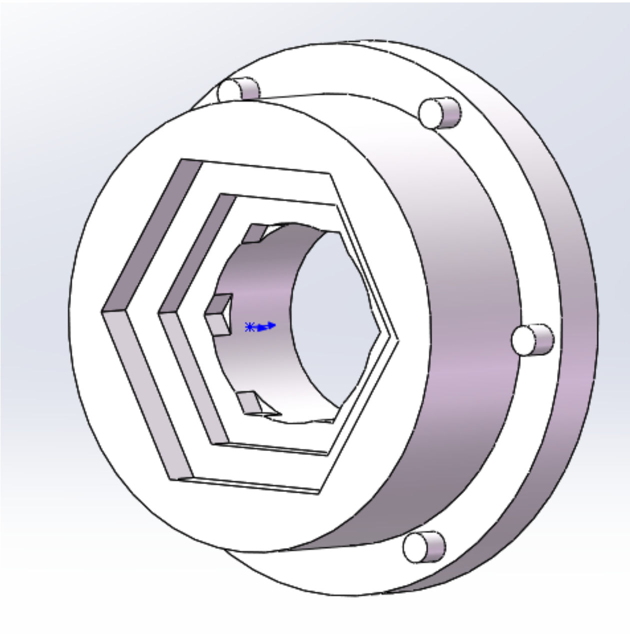

Figure 18. The 3D view of the pushing head

In fact, the pushing head can be united with the stem, but in my case, I made these two parts separated for two reasons. One reason is it is possible to put a sensor between the push head and the stem and can measure some datum interested, this part will be introduced later.

The another reason is that in this case it is possible to change another pushing head which is capable of operating with other dimensions of nuts which increasing the possibilities of this machine. Of course the target nut dimensions of changed pushing head should be incorporated with the remain part of the system.

The 3D view of the pushing head is shown in figure 18. It can be seen it is composed of a relative thin cylinder based component, the axial length is smaller than the diameter and a with six cylinder extrusions in it. The latter is used to connect to the stem. The six extrusions are in charging of translate the torque.

And the more important part, the former cylinder, is a hollow cylinder. The idea is to put part of the nuts inside the cylinder so to translate the torque to rotate it. It can be seen that the holes on the cylinder is in hexagon shape of three different dimensions, the bigger one is put on the outsider, so these hoses is able to keep the nuts with different size, and the perfect fit of hexagon shape is able to pushing the nut to rotate.

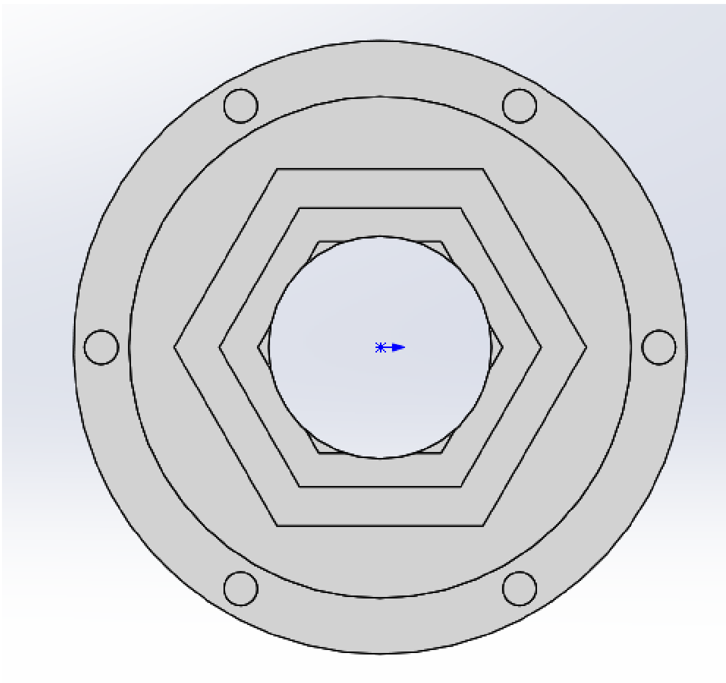

Figure 19. The front view of pushing head

Reminder that the dimensions of the three hexagon holes are little bigger than the related nuts, so there will be a very small gap can compensation of the dimension tolerance of the nut which will be a common phenomenon during industry process. And the height of the hexagon holes is about one third of the related nut height. And from the figure we can see that if the three dimensions selected are very close, it is possible to share the hexagon hole between two different nuts or even three, and also, if the three dimensions are way to long from each other, when we are to tighten the nuts with smallest dimension, there is a danger for the cylinder pushing head to hit the extrusions close to the bolt. So one limitation of this machine is that at the area where nut to be tightening, the around should be no extrusions to hit the pushing head.

And the total heights of the three hexagon holes should not exceed the height of the nuts, or the front plane of the pushing head will arrive the work piece before the nuts fit inside the holes. In our case 10 mm is selected since the height of M12 nuts has a height of 10.8 mm. In figure 19 we can see that in the middle there is a cylindrical hole behind the three hexagon holes, and its diameter is 20mm which is close to the dimension of the third hexagon hole and makes the area of 'walls' after the hole is reduced. So another problem is going up to be carefully treat. This hole is the passage for the end of bolt at the end of tightening process, this part pass through the nut and will extrude about 2 pitches. As a result, if the biggest nuts and smallest nuts are to far, the application should be careful. In the mentioned case, the extrusion of bolt after the nut should smaller than the second hexagon hole height, so we don't need to make a cylinder hole too bigger to exceed the third hexagon shape. If not, the three dimensions of nuts should be changed.

2.4 The connecting ring

The connecting ring is the component connect the pushing head to the stem in case that we separate the stem and pushing head in two individual part which the reason is demonstrated in section 2.4, the function also includes the transferring of the torque.

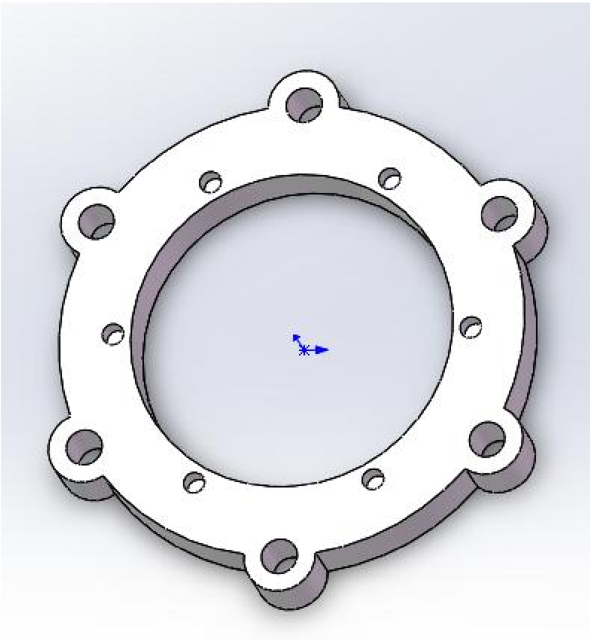

Figure 20. The connecting ring

The connecting ring is a simple ring with some holes on it . the pushing head is passing through the middle hole, and the front face connecting ring in figure 20 is connect with the pushing head since the small holes matches the extrusions of pushing head. And the six holes in the periphery will connect to same structure in stem through bolts. This six holes will also guarantee the symmetry and so the pressure distribution.

2.5 The stem

The stem is the parts connect the pushing head to the propulsion system. It is a cylindrical part which shows some function in both end.

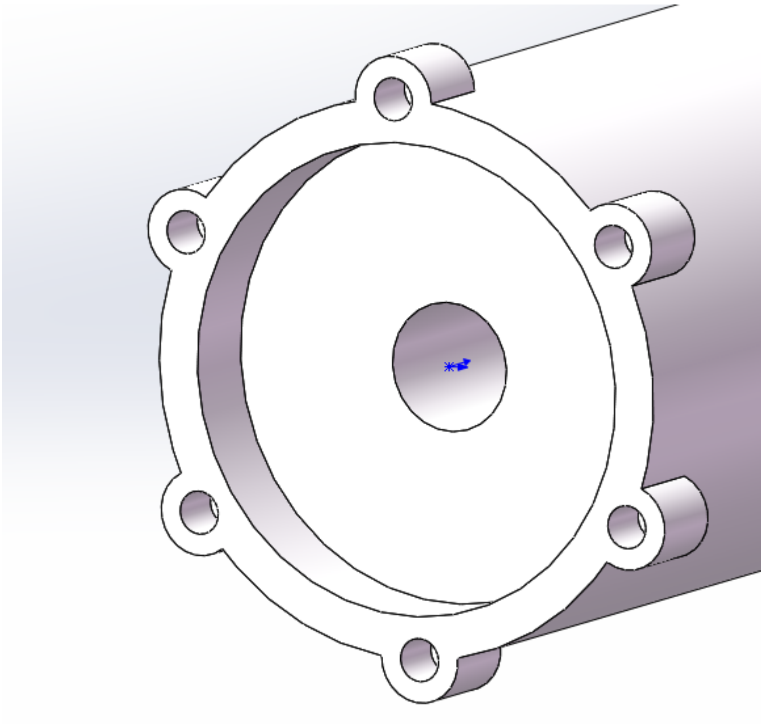

Figure 21. The stem lower end

The lower end is the end to connect pushing head with connecting ring, and it can be seen that in the periphery there are the holes matches the holes around the connecting ring, also the surface contact the pushing head is there. In the middle there is a hole to the other end, this hole can reduce the weigh of the whole stem, so to reduce the effort of propulsion system, also it can provide the space for the lubricating channels and wires for sensors and the space for the nut guider core and nut guider sleeve which will be introduced later.

Actually after the connection, there can be a gap of 10 mm between the pushing head and the stem, also this gap can be eliminate by reduce the annular part in the front if it is not necessary.

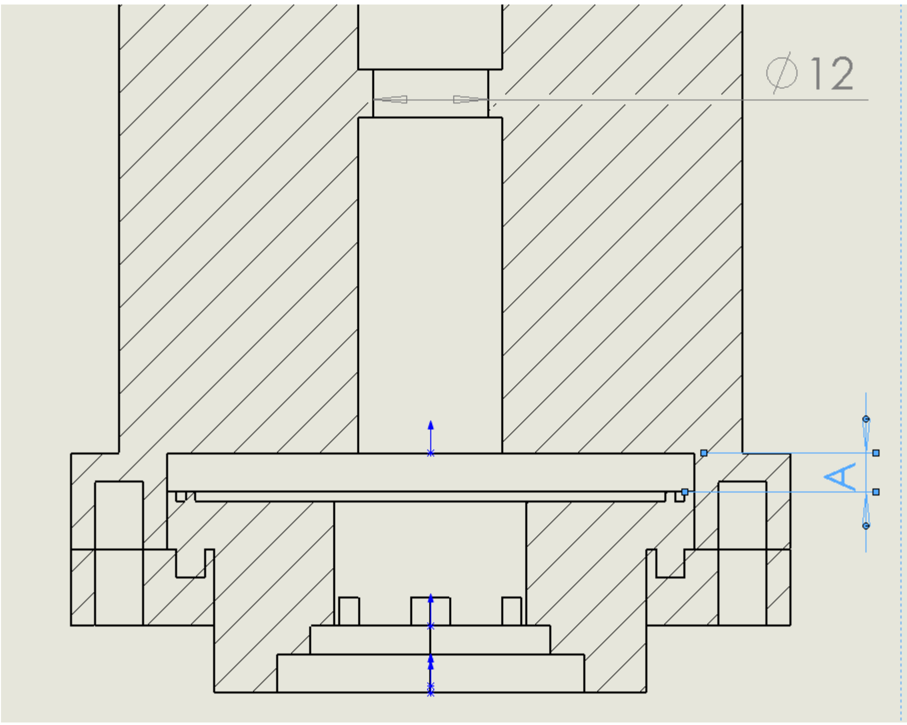

Figure 22. Section view after assemble of pushing head and stem

In figure, a section view after assembly of pushing head and stem with connecting ring is shown. The bottom component is pushing head, the outer one is connecting ring and the upper one is the stem. In this figure, there is a distance A indicates the distance between pushing head and the stem, A is 10mm in this design, this distance and the hole in the middle will form a annular gap where we can put a sensor with diaphragm which is able to measure the pressure between pushing head and stem.

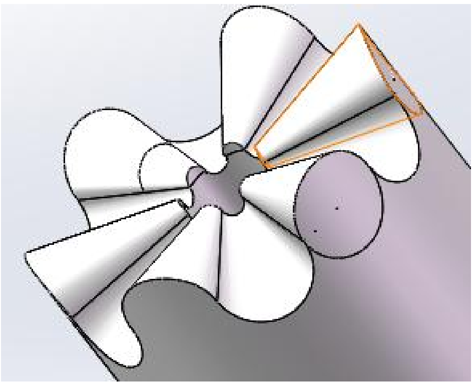

Figure 23. The upper end of the stem

The upper end of the stem is connect to the propulsion system. In fact the stem should be long enough to passing the distance of about half meter from the work piece to the propulsion system, this design is show the place where the end-stop occurs, and in reality the application may not in this form, but the idea is the same.

The end is shown some strange shape, and this shape is conjugate with the shape in propulsion system, there two profiles can match perfectly with each other to make a cylinder. This is very good for define a end-stop. The profile is equally distributed in 360 degrees, which means it is period change every 60 degree, in each 60 degree, a up and down profile are existing. At the lower end of the stem, the periphery have six holes, after assembly, the pushing head hexagon hole have six sides, the pushing head have six extrusions and on the upper end of stem and propulsion system, the profile is also change every 60 degrees. This means with proper arrange to make all the parts mentioned above have same phase, the symmetry will make the hexagon hole have same direction every time the stem hit the end-stop.

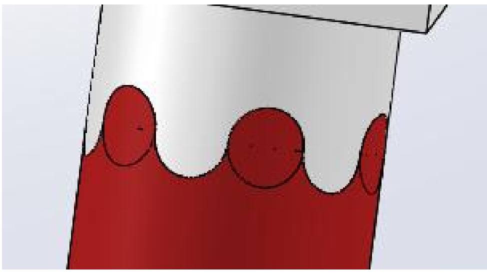

Figure 24. The conjugate profile of stem and end-stop

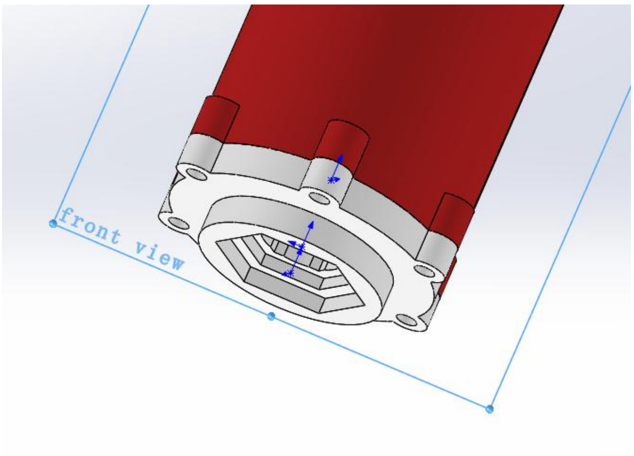

Figure 25. The direction of hexagon hole

With the same phases, we can always get the same results, figure 25 is the front view, it can be seen the hexagon hole is always with its width across the corners be parallel to the front view, and this is the direction set before design for the correct operation of the machine. The idea is the nut is always feed right below the stem and pushing head with this direction, so if we can assure the direction of hexagon hole matches the arrived nut, we don't need to rotate the stem before it goes down and reaches the nut, and this will strongly reduce the effort to control the timing and angle of rotation of stem before it reaches the nut. Any way, it is very important to keep this direction and we will always reach to this thanks to the profiles between stem and end-stop. The profile can be not limited to the drawn one with many conical surfaces, it can be any smooth surface repeating in every 60 degrees.

If without the profile, the contact between end-stop and the stem will be flat, and in order to keep the angular position of stem equal to the desired one at the end-stop, the stem must rotate to adjust the current position since every operation will end with different rotation numbers at the end of tightening. So more complex system and control strategy will needed. But with only physical solution with profile the problem could be solved. The only remain problem is that the profiles could be a little complex such as in this design, the manufacturing process of stem might be complex and costly. Some simple conjugate profiles could be adopted, such as triangles. But the main idea is to guarantee a smooth contact and rotation due to contact of the two conjugate profiles.

2.6 The nut feed channel

The nut feed channel work together with nut feeder in order to guarantee the direction of nut is the desired one, can it should of course work with the three different nuts. The nut feed channel is the channel transport the nut to nut feeder. And how to put nuts onto nut channel with required direction is not specified here. It should be say that some specific method must be take to make every nut has a same initial direction when put on to the nut feed channel, even though the nut is randomly stored in warehouse.

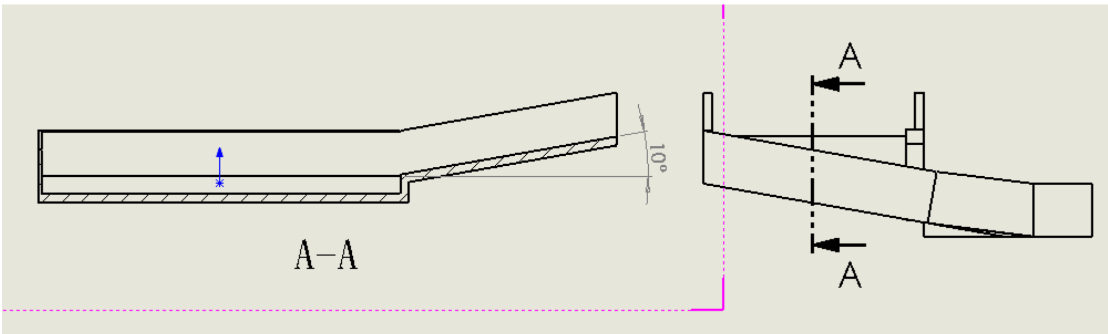

Figure 26. The section view of nut feed channel

The nut feed channel is mainly make of two panel and the working principle is through the movement on a slope. The two panels are all have a angle of 10 degree with respect to the horizontal plane. In picture 26, the section view is a right view, can it can be seem the right end, which is the start point of nut feed channel, from this point the channel is inclined 10 degree downward. As a result, the nut will slide down with this slope and hit the left end in figure 26.

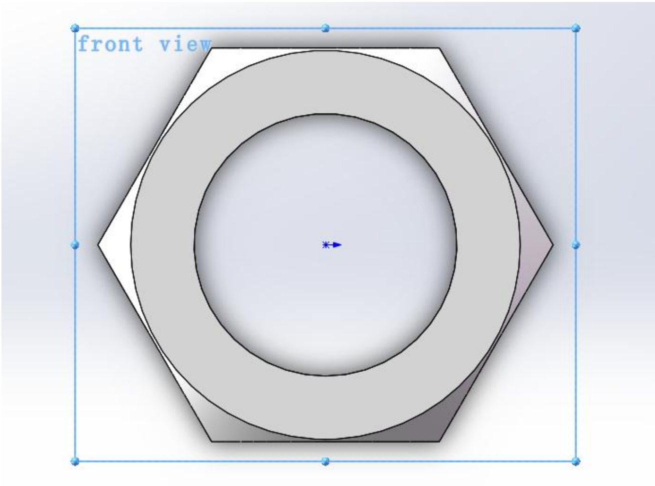

Figure 27. The desired direction of nut

The desired direction is the two sides upper and lower are parallel to the x direction. And if we put nut with this direction on the nut feed channel start point which is the right end on the section view in figure 26, the nut will slide to the left end, and the sides is parallel to the left end and will hit on it.

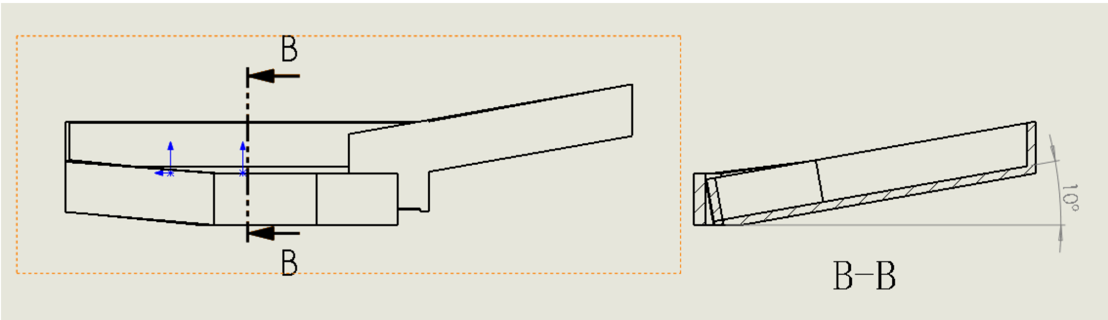

Figure 28. The section view on other side of channel

And in section view B-B, it can be seen that the left side is also form a 10 degree with the ground, so the nut will move downward. And it will mentioned above the remain movement is also base on the movement on a slope.

It can be got from physical equations that the force pushing the nut downward is mgsin(a), where mg is the gravity of nut and a is the slope which is 10 degree in our case. And the resistance force is due to friction and equal to fmgcos(a). Where the f is the coefficient of friction between channel and nut, mg still the gravity and a again the slope. In order to guarantee a downward, the down force must be greater than resistance force, which imply that the friction coefficient f should be no larger than tan(a) equals to 0.17 in our case. So the requirement of surface finishing of the channel is relative high. If the requirement can not be achieved, the slope should be increased in order to overcome the friction. But the coming problem is when nut reach the bottom, the hit effect will be more sever.

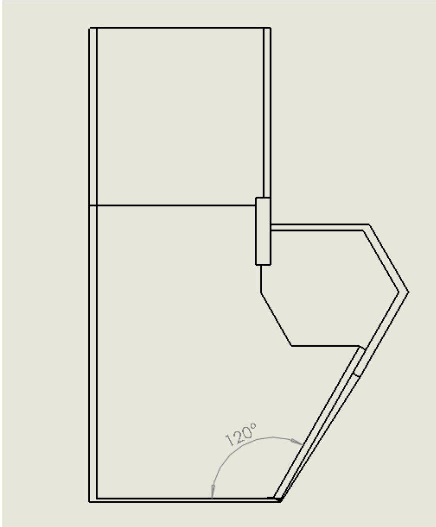

Figure 29. The top view of nut feeding channel

When nut finishes the first slope and it arrives the bottom in figure 29 no matter what dimension it is, and then it start the second slope and move to the right. After a while it reach the sides which form a 120 degree of the bottom side, so the nut will move along the new side since it is hexagon shape. All the three dimensions of nut can arrive to the right part which there is a more or less hexagon shape, this is a fence and the nut hit the fence and stop.

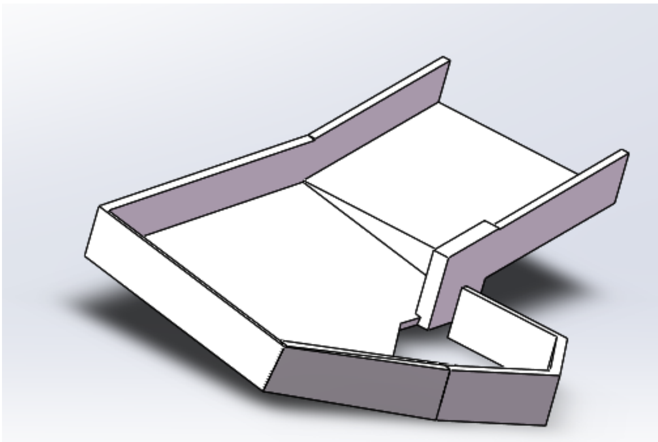

Figure 30. The 3D view of nut feeding channel

And since above the fenced hexagon is nothing, the nut will fall downward to the nut feeder just located below the this hole. The nut from been put on the channel to fall to the nut feeder, will always keep the desired direction, since it only undergoes translation but without rotation. In figure 30 it can be seen that the nut feed channel is not composed of parts with regular shape and direction, it can be optimized, such as the out looking, and also the slope can be modified into more smooth profile especially in the connect area between the two slopes.

2.7 The nut feeder

The nut feeder is firstly received the nut with desired direction from nut feed channel, it will also keep it with the same direction during whole operation.

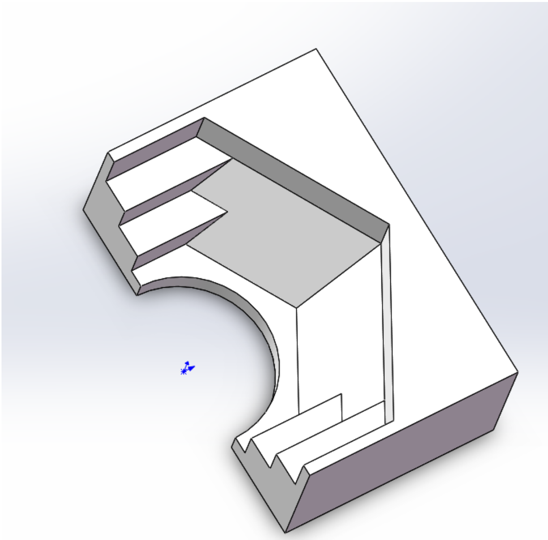

Figure 31. The nut feeder

The nut feeder should be pushed by propulsion system to arrive right below the pushing head and stem, and it didn't shown in the figure. The propulsion system can be the same one to feed and rotate stem located on the top, or it can be a individual one which can be located on the right but lower place consider many aspects.

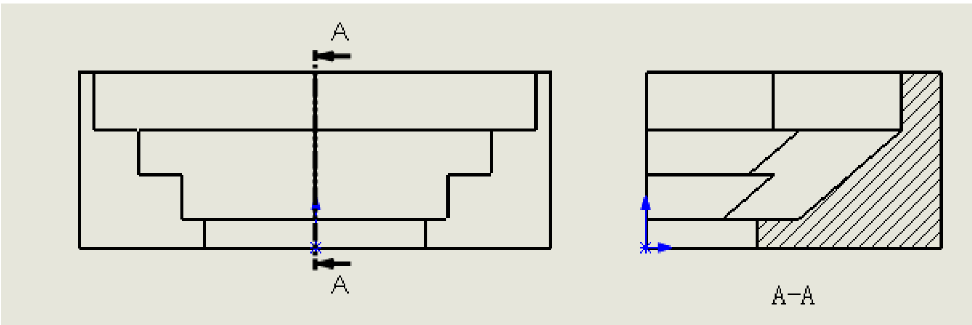

Figure 32. The section view of nut feeder

The nut feeder is same use multi stages to fulfill the three dimension nuts application. In the section view we can find the three stage, the deeper, the smaller, the dimensions are all related to the nut dimension, in order to keep fitly them in desired direction. The hexagon shape all have the same middle at the right side, and so the hexagon downward is half of the complete hexagon shape. Actually depend on the case the left side can be put more left and so the three downward stage is more than a half of hexagon shape, this help to sustain the nut.

And since the nut is slide from the nut feeding channel, it is supposed to locate firstly at the stage 1 with maximum dimension and contact the most right side. Thanks to the slope below the stage 1, the medium size and smallest size can slide downward until to where they should be, can in this way, the separation of three dimensions achieved, afterward, the three kind of nuts will meeting different end-stop, but make them all stop with symmetry shaft right below the pushing head.

Since the two smaller nuts are slide down to where they should be ,there should be some prevent structure to prevent them sliding outside the nut pusher. But the structure is not shown in the design, it share the same principle with something I will introduce later.

2.8 The nut end-stop

The nut is feeding toward the working position, and it will stop right below the pushing head thanks to the nut end-stop and some proper control strategy of propulsion system.

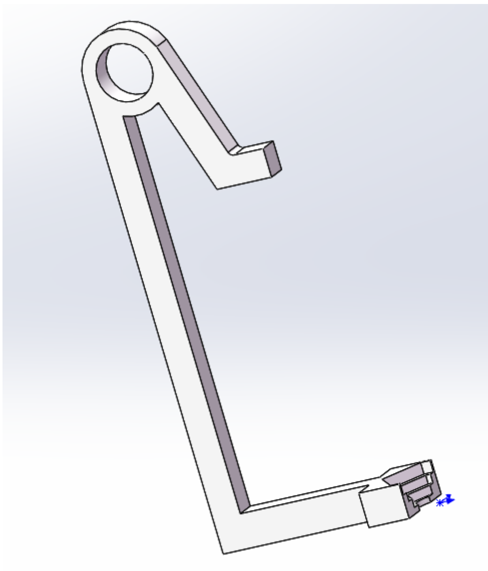

Figure 33. The nut end-stop

The nut end-stop is a relative big structure and mainly composed of two parts, the two parts are all connect to a upper center of rotation. the upper center of rotation is supported onto the frame and it can rotate about its shaft. This structure is called the nut end-stop because the bottom part is contributed to act as the end of feeding of nut. The detailed dimension is shown below.

The structure is the mirror of the nut feeder, but with a cut from right side, this cut make the structure somehow away from the middle axis and reduce the weight. The idea is the same, with three levels of 'walls', since different nut will located in different level with nut feeder, the different height will match to different end-stops, the bigger dimensions, the longer the end-stop.

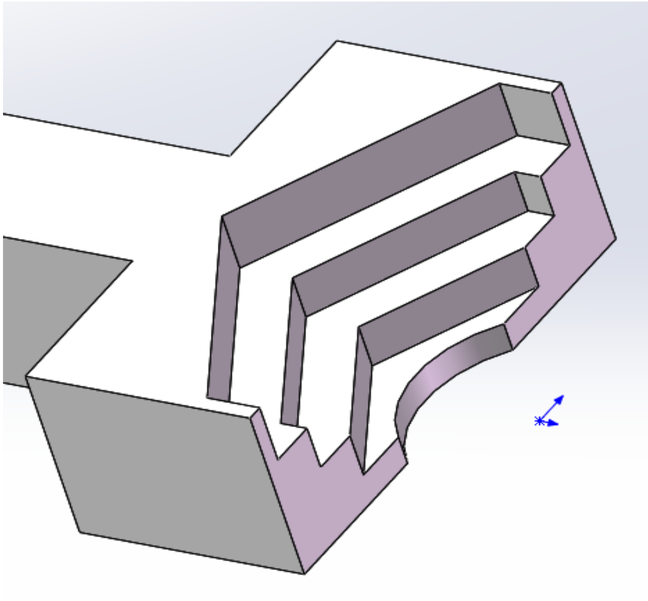

Figure 34. The end of feeding nut

And it is simple to understand, since the three different size nuts start with same axis and need to be ended at same axis, the bigger dimension nut will have its outer side results in further, the outer will always be the outer, so the end-stop of the biggest nut will locate more to the left.

And the cylindrical hole at the bottom share the same function of holes at bottom of nut feeder, is the passage of nut guider core and nut guider sleeve.

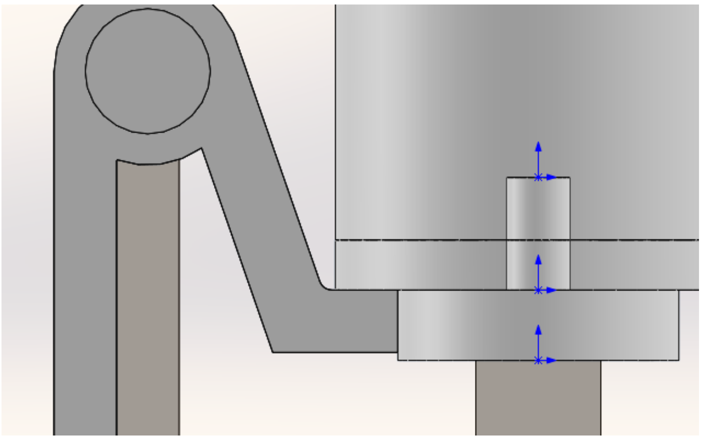

Figure 35. Rest position of nut end-stop and stem

When the stem moving down, the bottom end-stop will collision with end outer pushing head, can to solve this problem, the upper part works. As shown in figure 35, the end-stop upper part will contact with stem at connecting ring bottom surface, and with stem moving down, the contact part will be pushed downward and as a result it will rotate with the shaft on left-top. Actually all the nut end-stop is going to rotate under the pushing of stem, the need in only to verify when the nut end-stop is rotate to its maximum displacement, will the bottom part still collision with the pushing head.

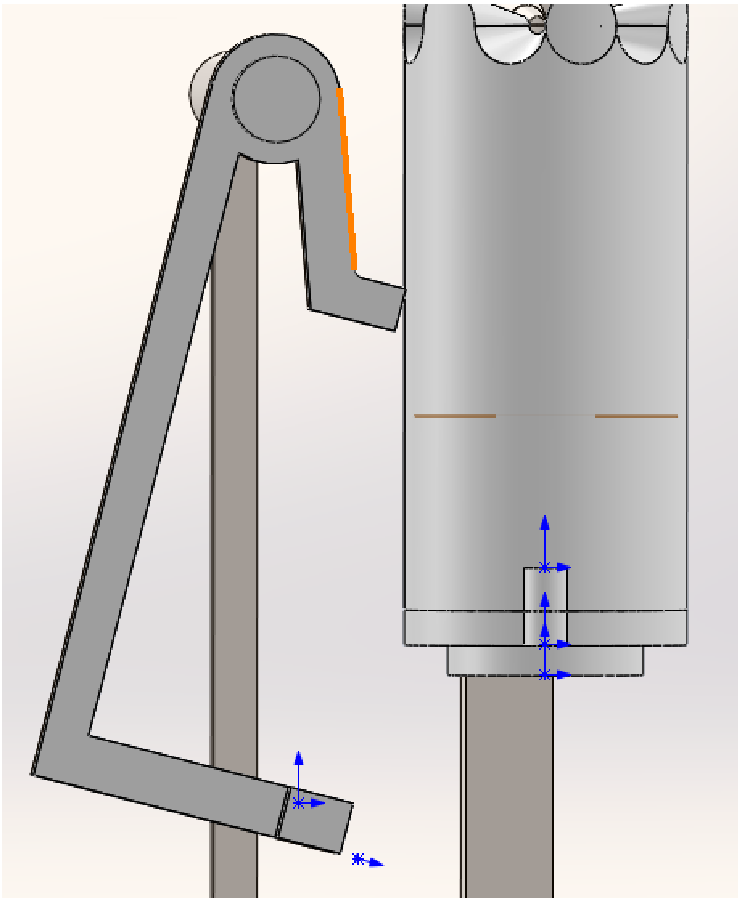

Figure 36. The maximum displacement of nut end-stop

With the simulation of solidworks, the result is in figure 36. When the nut end-stop reaches its maximum displacement, it means the upper part only have one single side which is tangent to the cylindrical surface of stem, use this to define the constraint and the result shows the nut end-stop rotates enough angle to guarantee the non- collision during operation. And after the tightening, during the up going of stem, the nut end-stop will return to original position due to gravity.

Also, this method is applied to the nut feeder to solve the problem. A similar structure is applied with some dam-board at side of nut feeder to guarantee the smaller nuts will not slide beyond the nut feeder, than when the nut feed start to move, the dam-board is pushed and rotate so it will not block the movement of nut feeder. And during its back, since this case gravity didn't help, it can be use the same method as before. So the when the front board is moving away, it connect to a behind board to rotate toward the nut feeder pathway, and then the nut feeder moving back, it will bush the behind board away from the pathway, this cause the front board to rotate to its original position, thus make a circulation.

2.9 The nut guider

Since when the nut feeder transports the nut until the end-stop, it will return to it's original position after a short time stay, other wise when the stem moving down, it will definitely collision with stem. And without the support of nut feeder, the nut will fall down since the support plane of the nut end-stop is less than half of a hexagon shape. So in this case, the nut guider works. The nut guider is some thin tubes which can pass through the middle hole of the stem, the pushing head and reach the nut before stem is going down. Of course the nut guider is delivered by propulsion system which belongs to the system upward. The then it will keep the nut not falling down after the backing of nut feeder.

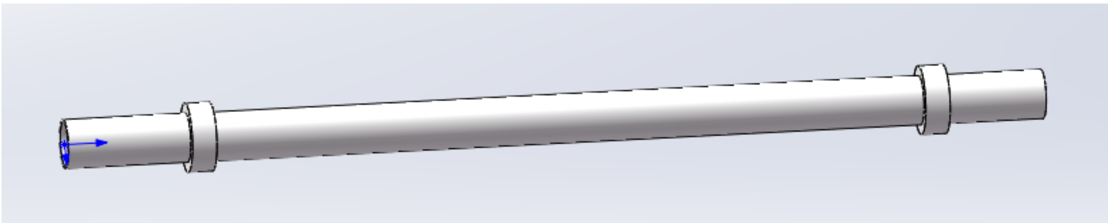

Figure 37. The nut guider sleeve

The nut guider is divided into two parts, the sleeve and the core. The sleeve is a hollow cylinder whose diameter is smaller than the smallest nut screw dimension the machine can operate with, and also for sure the mid hole of stem and pushing head, so it will go through the mid hole and reach the hole of nut. The nut guider sleeve have two annular extrusion which indicates the two end-stop. The left one is the up going end-stop and the right one is the down going end-stop.

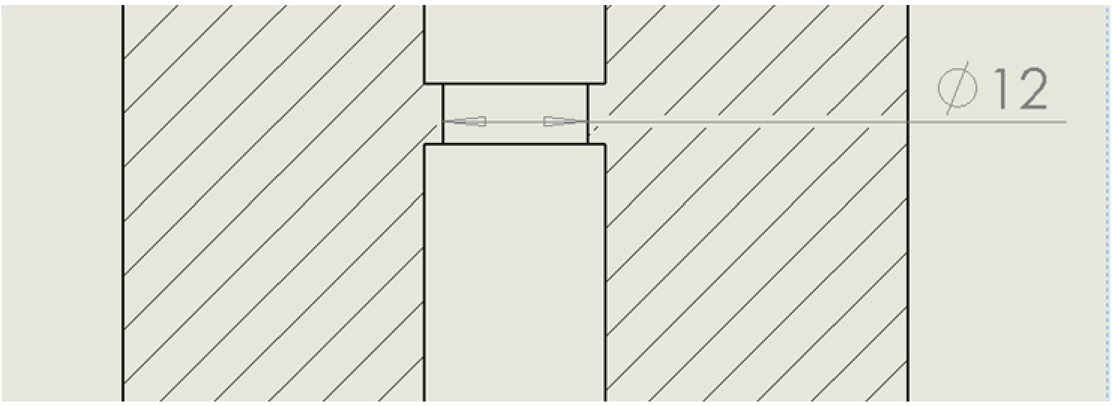

Figure 38. The mid and extrusion of stem

Inside the mid hole of the stem, the hole diameter is 15 mm, and on a certain position, the diameter is reduced to 12 mm, this change last for 3mm in length so form a annular extrusion. And the nut guider sleeve has a normal diameter 10 mm which is small than the minimum diameter of a M12 11.73 mm, and the left and right two end-stops are of diameter of 14 mm. So when going up and down the sleeve will hit the same extrusion inside stem mid hole, so the distance from left end to the right end-stop is should fulfill the distance to go through the hole of nuts while the distance between left end and left end-stop is also important and the usage will be introduced later.

The second part of the nut guider is the core.

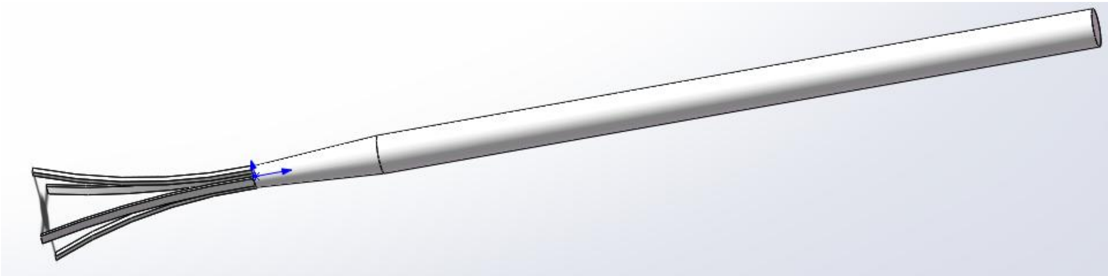

Figure 39. The nut guider core

The core again is a cylinder based structure and is thinner than the sleeve, so it can go through the middle hole of the nut guider sleeve. And on the left end of nut guider core, there is some structure with particular shape. Those are made of some flexible metal or plastic, they connect to the core and spread out uniformly, and looking from left, the spread outer line can be treated as a circular, and this circular has a diameter larger than all the nut screw dimension can be operated in this machine, so it go through the sleeve and on the end, the flexible part spread to a dimension larger than then nut, so when nut feeder leaves, the nut will contact with the flexible part and remain there.

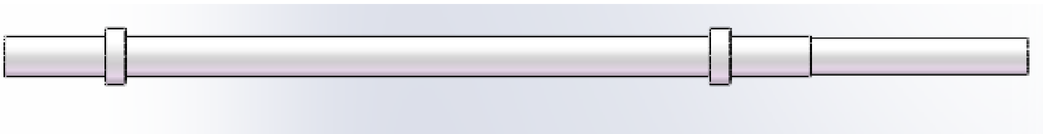

Figure 40. Rest position of nut guider

The rest position is that the core is inside the sleeve, and the flexible end is also inside the sleeve but very close to the left end of the sleeve. The flexible is spreading but it contact the sleeve, it will generate a pressure which push the sleeve and core stick together. Then the propulsion system direct act on the nut guider core, the core is pushed to go downward. But since there is a certain pressure between the sleeve and the core, there will also be a certain value of friction, this friction will make the sleeve do the same movements as the core. The whole nut guider move down until the sleeve meet the annular extrusion inside the mid hole of stem, then the further pushing on the core will make the relative motion between sleeve and core, since sleeve is stick to still and the core is still pushed to going down, as a result, the flexible part of core start to coming out.

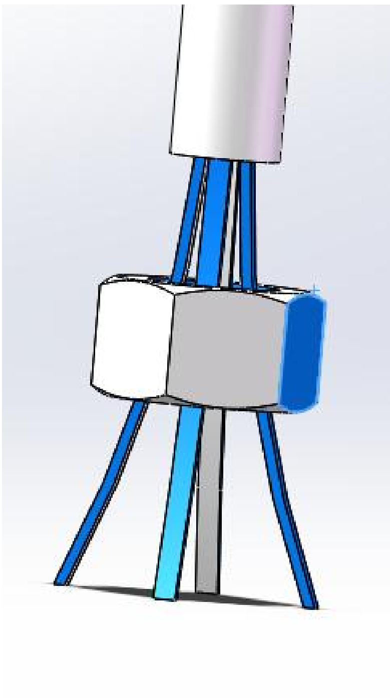

Figure 41 The keep of nut M12

As mentioned before, at the downward end-stop, the sleeve length is enough to go through the hole of nut, so the coming out flexible part spread to a dimension larger than the nut screw hole, so the nut is keep upon the flexible part. And since the gravity of nut is small, it's not possible for the not to converge the flexible part by gravity and it will stay with the nut guider core at end-stop position. That's how the system works.

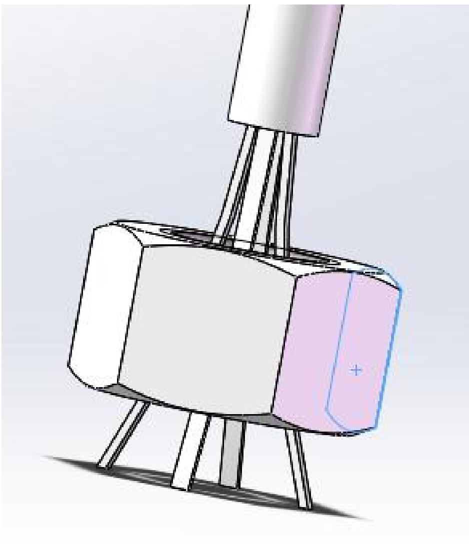

Figure 42 The keep of nut M20

And since the distribution of the flexible part is uniform, so after the small fall down and contact will the flexible part, the nut is still not involved in rotation which means it will remain it’s desired direction. And then the stem moving down, the nut is fit into the hexagon holes of pushing head, stem keeping going down, the pushing force is large enough to convergent the flexible part and make the nut go through the flexible part, up to now, the mission of nut guider is finished.’

And after the tightening, the stem start to go up, at the same time, the propulsion system start to pull the nut guider core upwards. With the up going, the flexible part meet the sleeve, but at the beginning the force is not enough to convergent the flexible part into the sleeve, so the spread flexible part push the sleeve going up. Until the sleeve reaches it’s end-stop, then the resistance force is big enough to make the flexible part to convergent and go into the sleeve just like the original position. So the dimension mentioned above, the distance of sleeve left end to it’s left end-stop will influence the power of going up. Since if the distance is short, it means the convergent will occur later and the friction power is less, but the drawback is the possibility to have some length of flexible part remains outside the sleeve when the core stops.

2.10 The working process

So up to now, the working process of the machine is clear, it starts when the work piece together with desired bolt arrived the target position where the axis of stem coincide with the axis of the bolt. Then since the machine have already received the type of nuts should be used, the process start with the put of related nut onto the nut feeding channel, of course with the desired direction.

The nut slide follow the wall and ground of nut feeding channel and fall onto the nut feeder with related depth, the smaller, the deeper. Then the propulsion system activates the nut feeder go direct until it reaches nut end-stop.

Then the nut guider core is pushed downwards together with not guider sleeve to keep the nut on the flexible part of nut guider core as discussed in section 2.9, after wards the nut feeder return while the stem start to going down. The pushing head fit with the nut and start to rotate, it reach the bolt and finish the tightening. Then it moves upwards to initial position. The whole process has been simulated in solidworks, and it turns out to be no collisions during the operation which implied the theoretical feasible, but there are still some problems need to be improved or taken into account.

The whole process is described above, some control is through physical and mechanical method, and the remains should be realize through electrical ways which will be discussed in section 3.

2.11 For optimization

This machine, or this system is only a part of the complete bolt tightening, since it starts when the work piece is already in position. So only when the system in charge of feeding of work piece and insert of bolt are connected to this design, the whole system is finished.

The application of this machine is still meet some limitations, it limit the work piece shape to be flat, it limit the usable dimension range of nuts, so some improvements can be done to optimize the operation condition. For example, the hushing head now is a closed shape with hole, maybe it can be reduce to only two walls just like the gripper in robot arm.

There are some process need to be experimentally proceed in order to see if their will be some problem during real manufacturing. For example, the nut feeding channel is based on sliding which the real condition may far away from theoretical due to roughness, resistance force, the nut going out from nut feeding channel maybe not in desired direction which will totally destroy the process. Another possible cause can be during the contact of nut and nut guider core flexible part, the flexible part may not spread uniformly, and the nut may undergo a displacement due to the friction when the nut feeder going back. So the ways to keep the nut always in desired direction is always need to be develop, or the develop of complex control strategy with low cost.

Section 3: Data Measurement

As mentioned in section 1, the cyber physical system is one of the key points for Industry 4.0, and this cyber physical system is worked based on numerical sensors and transducers, and so how to use these sensors and transducers and what physical quantity is need to be measured is the next question to be solved for an Industry 4.0 application. In this section, we will discuss about based on the bolt/nut tightening machine above, which quantities should we measure and how to measure it. And in next section 4, the usage of the data measured is going to be discussed.

3.1 sensors and transducers

To measure a physical quantity, the more technology way with high efficiency, high accuracy, high level of automation must be the sensors and transducers. Sensors and transducers have the same Chinese translation but actually they have difference since they got two separate names.

First of all, no matter sensors or transducers, they share the same basic function is that they measure a physical quantity as input, and then they give an output in the form easy to be use and recognize by human, and also there is a relation function link the output to the input. In another wards, with the output of the senor or transducer, there is a function or some equations help us to find the original physical quantity, so it can be used or monitored.

Sensors and transducers have been the necessary part in industry, they can take part in the control process or diagnostic process, they can also used to alert where an emergency takes place, its development is quickly in recent decades, and based on it's design, the result they gives could be in very high accuracy and stability. So depend on casing by casing, different level of sensors and transducers can be selected, for application with high accuracy needed, some more advanced sensors should be used. As refer to our case, the accuracy could be not so high since the sensors and transducers are mostly helped to guarantee the preload of the tightening, where the number is not the most important, the magnitude is more important, so the relative sensor could be shown of some degree of inaccuracy, so the most common sensors and transducers can be used.

So sensors and transducers share the same working purpose, can there is still be a difference in between. The sensors are more of a structure component and is usually not so complicated, it will measure the quantity through some physical ways. Usually there will be some physical deformations and causes electric properties to change, the resistance for example. Or it can go through chemical process which also lead to change of electric properties like resistance. So the common face they share is that it works with the physical properties changing. As a result, with certain circuit, we will get a variation of current which present the change of quantity we measured.

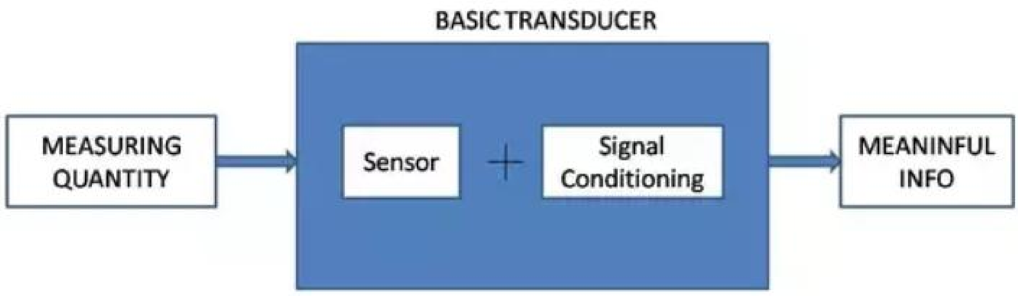

Figure 42. The structure of a transducer

As for the transducer, it is more than a sensor which means it usually contain a sensor. As mentioned above, the sensors work with change of its physical properties, and this means that the output signal is limited because it is related to that physical properties, the current and resistance in last case. And a transducer can not only measure a quantity, but to give an output in the form we wanted, for example, a digital signal. The idea is to combine the sensors and some signal conditioning component to form a structural form, the sensors still give a current out, and signal conditioning can do some coding, translating or selecting and give a output in whatever form we want, the analog plot, the square wave or a sinusoid wave. So in a transducer, there will be some exchange of power with it since it modify the original result the sensor give.

3.2 The pressures need to be measured

A pressure sensor is the most common sensor to be used in machine no matter nowadays or in Industry 4.0. And refer to the bolt/nut tightening machine above, there are some pressures we are interested.

Firstly the preload is the most interested quantity. In order to measure the preload, the sensors should be put or between the two work pieces, or be put in between the nut and work piece, or even in between the nut and screws. But unfortunately all the three positions mentioned above are not feasible, since the sensor should be put into the position then plug out every time we finish a work piece and go to the next one, and also it is hard to repeat this process. So the idea is to measure the pressure in between the pushing head and nut, the sensors can be mounted to the lower surface of pushing head and attach to it while when finishing the tightening, it can going back with the pushing head. The idea is good and applicable in a common tightening machine. But in my design, since the nut with different dimension will contact with different lower surface of the pushing head, we can't use a single one sensor to measure the contact pressure for all the three dimensions conditions.

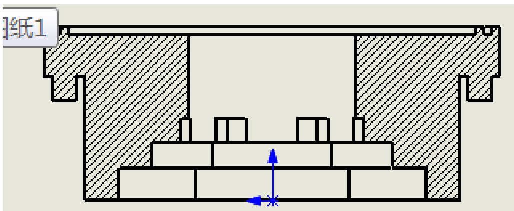

Figure 43. The contact surfaces in pushing head

In figure 43 we can see the three horizontal contact surfaces for different nuts, also it can be seen each surface is a annular one with not too march thickness. So the other problem is the space for the sensor to mount is small on each contact surface, and it will influence the normal working of sensors and also the accuracy of the results.

So the solution is to make the pushing head and stem in two different parts, and connect them with the connecting ring ,so we will have a larger annular space for mounting the pressure sensor.

In figure 44 the section of assembly part pushing head, stem and connecting ring is shown, and since there is a gap between pushing head and stem which indicates with letter A in the section view, the space for sensor in much bigger compared to mounting between nut and pushing head. Also in the figure 44, in the side of the mounting space, there is an annular slot helps to mounting. Since there is a torque and force transmission between stem and pushing head, if we direct connect the pushing head with a sensor with a diaphragm for example, and then connect the diaphragm to the pushing head, the system is also work but with some problems. The problem is that when in rest condition, the diaphragm is deformed mainly tension due to the gravity and also during up going of the stem, the acceleration will also cause a tension of the diaphragm. The tension process may cause damage to the sensor and influence the result. Also, since it will give some outputs even there is no pressure between pushing head and stem, the results should be selected and modified to be used.

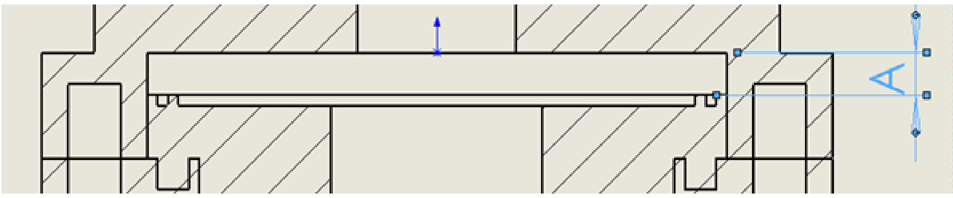

Figure 44. The space for sensor mounting

To solve this limitation, the connecting ring is introduced, since the connecting ring is mounted to support the pushing head, in the two working conditions mentioned above will not exist anymore, since the gravity and up going acceleration will be balanced by the support force generated from the contact of connecting and pushing head, so the diaphragm will not undergo a tension process, it will or in the rest shape, or be compressed, so we don't need more adjusting of the output signals.

Another position where we can measure the preload is where between the stem and the propulsion system. Since because of the force balance, the contact pressure upstream should be same as the contact pressure downwards. For example there could be a similar structure like mentioned in last paragraph, but between the stem and the pushing element. And if the propulsion system is in the form of hydraulic or pneumatic, the pressure in the actuator chamber is the pressure we want, and the fluid pressure is way more easy to be measured. But for application this to my design, there are some limitations.

As described in section 2, during the downwards of stem, there are two more actions will influence pressure sensor results. One is the contact of stem and nut end-stop, since when stem started to going down, it needs to push the nut end-stop outsides, this will generate an additional pressure which will measure between the propulsion system and stem. Also during the up going process, the nut end-stop return to it's original position due to gravity, this will also pushes the stem up. A second action is due to the nut guider core, since the after pushing head fits the nut, some more force, or pressure in another word should be implemented in order to make the flexible part of nut guider core convergent and make the nut passing. All these two actions will generate some other changes in a p-t plot the sensor generates. And also due to frictions and resistances, the measured value would be larger than the real pressure the bolt and nut undergo. So if the upstream pressure sensor is going to be applied, some more modifications are needed to treat the result.

A second pressure could be the pressure between the propulsion system and the nut feeder, and it will equals to the feeding force. The method could be the same as the pressure used in the first application, since it is also a contact pressure. But in this condition there will no gravity needed to be pay attention, if the pressure senor if of good quality, it can direct connecting in between the propulsion system and the nut feeder. As a result, it will not have the function of a sensor, it will also have the function to transmit force.

And if necessary, the pressure between the nut guider sleeve and the stem during the down going process can be measured. The nut guider sleeve and stem will contact with stem up to it's end stop, the pressure can be measured in order to see the condition of working.

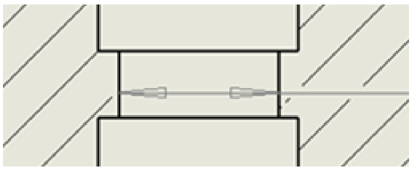

Figure 45. The contact surface between stem and nut guider sleeve

In figure 45, two surface is formed due to the variation of diameter, the two surfaces are contacts surfaces between stem and nut guider sleeve to form a end-stop for nut guider sleeve, the upper surface is end-stop for down going and vice versa. Since we only need the pressure during the down going, a pressure sensor could be mounted on the upper contact surface. It can be seen the space is very small and the annular surface is of thickness 3 mm, so if necessary a slot can be made to extend the thickness of the annular contact surface, so to guarantee the enough space for mount a pressure sensor.

3.3 The pressure sensors and strain gauge

The pressure sensors a mainly based on strain gauge. The most common one is the resistance strain gauge. The working principle of a strain gauge is that the conductor and semi conductor will undergo mechanical deformation while external force applied to it, also this external force will equivalent to a pressure. The mechanical deformation will cause the resistance to change.

$$R = \rho \frac{l}{A} \qquad \textbf{(equation 1)}$$

The equation 1 is the expression of electrical resistance of a conductor, the R is the resistance, the l is the length of the conductor, A is the cross section of the conductor, and ρ is the electrical resistivity. And assume it under goes an axial force F so be compression or tension, the l A and ρ in equation 1 will all change due to the deformation, and the differential equation to express the change of the resistance with these three variables is:

$$\frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho} \quad \textbf{(equation 2)}$$

And also the axial strain of the material is defined as ξ = dl/l. And since the area A is calculated as 2*pi*r^2, it can be get easily that the radial strain dA/A =2 dr/r. Where the r is the radius of the cross section if assumed it is a circle. And from the area of material mechanics, when the material is undergo a axial tension, the length is increasing while the radial is reducing, combined the two strain expression, we can get the relation between strain of radial and axial.

$$\frac{dr}{r} = -\mu\frac{dl}{l} = -\mu\xi \quad \textbf{(equation 3)}$$

In equation 3, the symbol μ is the passion ratio of the material and the minus sign indicates the two change is in different direction. So we substitute all this back into equation 2 and finally we will get:

$$\frac{dR}{R} = (1 + 2\mu)\frac{dl}{l} + \frac{d\rho}{\rho} \quad \textbf{(equation 4)}$$

And from this equation we can see how the resistance will change with the change of length, the sensitivity K is the variable describe the property mentioned before, it is defined and can be derived as :

$$K = \frac{dR}{R} / \frac{dl}{l} = (1 + 2\mu) + \frac{d\rho/\rho}{\xi} \quad \textbf{(equation 5)}$$

The first term 1+2μ is a constant and depend on the material, especially its change in geometry shape, and the second term is depend on the changing of electrical resistivity when after the deformation. The numerator dρ/ρ depend on many things, for a metal conductor, it is proportional to the term (1-2μ) relate to the shape changing, and also proportion to the axial strain ξ. And also it is related to the material property and the process it is made which is relative complicated.

Based on the principle described above, the strain gauge can structure can be introduced. It is mainly composed of four parts. The most important part is the middle one, the grid. The grid is made of conductors or semi-conductors and it have the property which described by the equation before, it use conductors with diameter of 0.025 mm which is relative small, and the total length is not too long, it has a value of resistance usually higher than 100 ohm.

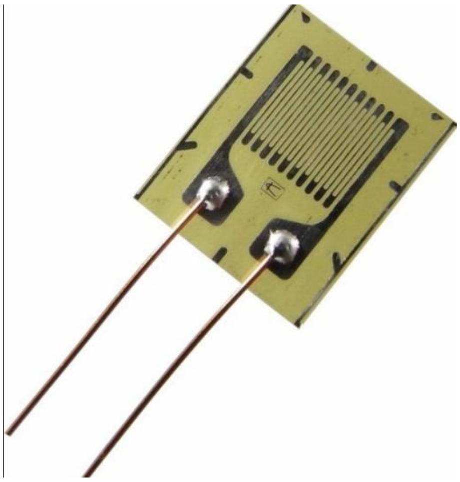

Figure 46. The strain gauge

Below the grid, there is a big square yellow part, this is the base. Base is used to support the grid and make it away from other electrical phenomenon. And upon the grid, there is a protection layer which prevent the grid away from being corrosion and being damped. And the last two wires prolonged beyond the base is linked to an external circuit with voltage supply. So the change of resistance of grid will make a change of current which we can easily measure with an ampere meter.

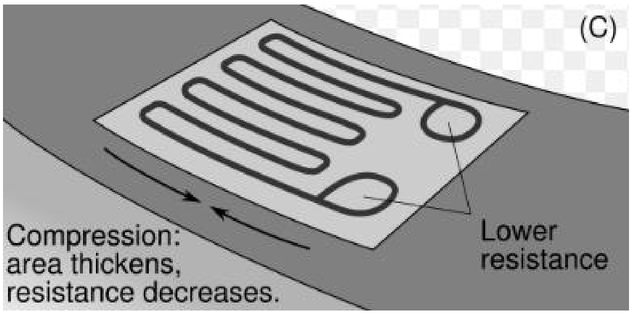

Figure 47. The working condition of a strain gauge

The strain gauge is a thin panel and it can be directly used by putting, connecting or adhering it to the surface to be measured. the surface will undergo a strain, or in another word a displacement under the external force or torque, since the strain gauge is in contact with the surface, the strain gauge especially the resistance grid will also suffer the same strain, this will cause the changing of resistance.

For example in figure 47, the surface is going raise in it's middle part, so the resistance grip will be in tension, according to the equations, the lengthen in axial direction and shorten in radial direction will cause a increasing in resistance, so from the external circuit we can read a increasing of current. And in figure 48, we see the opposite condition where the grid is in compression, and the results are in opposite direction.

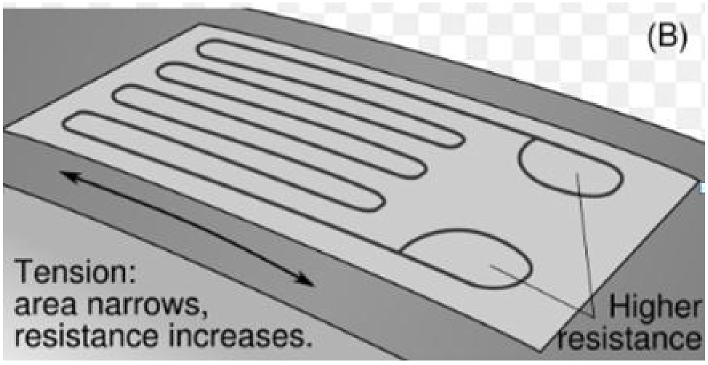

Figure 48. Another working condition of strain gauge

Another type of application of strain gauge is to connect it with a sensitive structure. This sensitive structure is sensitive to some physical quantities. For example, the spring and diaphragm are sensitive to the force applied, which results in a deformation. And also the mercury is sensitive to the temperature and can expand under high temperature. So the idea is use a proper method, proper material and proper structure, the desired physical quantities, such as pressure, temperature, the humidity can be transform into a certain strain, then the strain gauge works. It undergoes the same quantity of strain and it will give the related resistance change. So in theory, the strain gauge can be composed to sensors which are capable of measure everything.

During application, since the change of resistance of a strain gauge is not too much, so if it is directed link to a voltage source, the changing of current will be relative small, in some case it is even hardly to recognize the changing. One way is to have many strain gauges in series, so the total resistance change would be large. But it is really an inefficient way since in order to make resistance change big, it means with multiple strain gauges in series the total resistance of grid is also big, so in order to have a certain value of current, the voltage supply source need to be of high voltage.

The another way is to using a specific circuit to enlarge the changing. With a bridge configuration it is possible to reach the target.

The bridge structure is shown in figure 49 where we can see four resistances, and assume that R2 is the resistance of the grid inside the strain gauge. The other three resistance are constant, while R2 is change due to the strain gauge deformation. The strain of the grid is ξ and the strain is a function of pressure, in this application, it can also be other quantities such as torque. So the relation $\Delta P = f(\xi)$ is get, and then the resistance $R2 = f(\Delta P)$ can be write, so finally $R1 = f(\xi)$. And the four resistance are connect so that R1 and R2 are in series, R3 and R4 are in series, and the two group are parallel to each other, and they all connect to the external voltage source V_{DD} which is known. The v_D is the voltage between the two parallel circuits and is the one we need to measure, this quantity present the information from strain gauge.

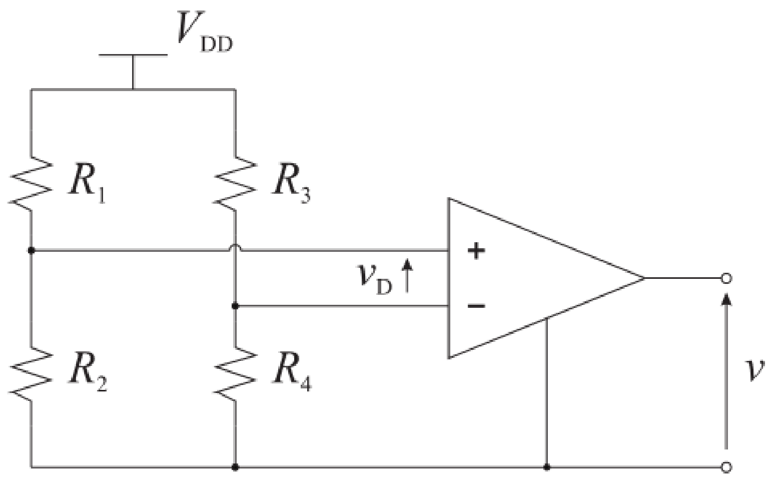

Figure 49. The circuit outside the strain gauge

Firstly the other three resistance are selected, and then the nominal resistance of the strain gauge is set to be equal to the other resistance. Actually the four resistance should form a relationship that R1*R4 equals R2*R3, and to simplified situation, the four resistances are set to the same value. The nominal means that the strain gauge doesn't undergo any deformation, neither traction nor compression.

Then from the circuit, the relationship of V_{DD} and v_D can be write.

$$\mathbf{v_D = V_{DD}\frac{R2}{R1+R2} - V_{DD}\frac{R4}{R3+RA}} \quad \textbf{(equation 6)}$$

Substitute R2= R+ΔR and R1, R3, R4 equals to R

$$\mathbf{v_D = V_{DD}\frac{\Delta R}{2(2R+\Delta R)}} \quad \textbf{(equation 7)}$$

If neglect the ΔR in the denominator we get a linear relation between V_{DD} and v_D. and if we put don't have only one strain gauge, assume that R3 is also a resistance grid of strain gauge, it is possible to improve the output. Substitute R2 and R3 equals to R+ΔR, and the result will be double as the result in equation 7, in this way, we double the amplitude of result.

And if we put two strain gauge on the internal surface, the two related resistances are R2 and R3, and then we put two other strain gauge on the external surface and related to R1 and R4. When the surface is curved, the internal surface will tract and external surface compressed, which induced R1 and R4 reduced, R2 and R3 increase. Substitute R1 and R4 equals R-ΔR and R3 and R3 equals R+ΔR in equation 7, we will get a four times the result in equation 7. So by increasing the number of strain gauges, we can further amplifier the magnitude of results we get.

In order to measure the pressure, the strain gauge is connect to proper things. Firstly in order to measure the contact pressure between pushing head and stem, and also between propulsion system and nut feeder, the strain gauge can be connect to a diaphragm spring.

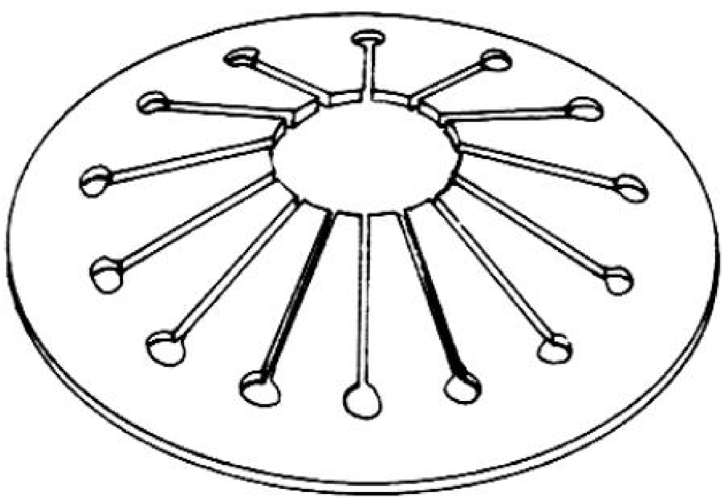

Figure 50. The diaphragm spring

The diaphragm spring is in conical shape with hollow mid which is perfectly match the gap between pushing head and stem, also between stem and nut guider sleeve.

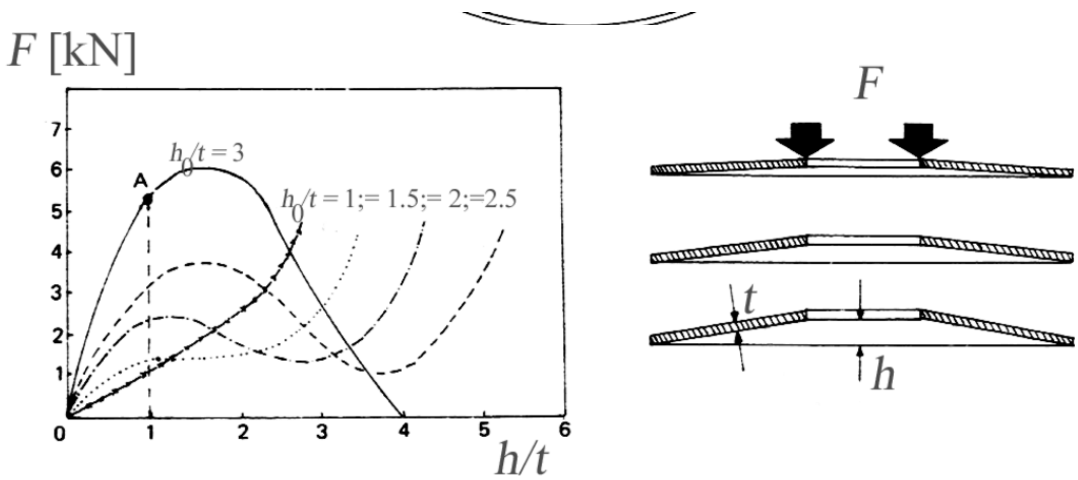

Figure 51. The dimension and load profile

The diaphragm spring is described by two dimensions, which are the height and thickness, during operation the thickness is constant and height is changing due to the external load F. After selection of proper size of the diaphragm, the related force displacement characteristic is defined, so the displacement is connect to the external force. And with the know cross section area as A, the pressure is calculated by F/A. and actually in some usage the force itself is more useful than pressure, and since during the transmission the whole force is applied to the diaphragm spring, the result of the sensor can also be of the quantity of force. And this can be the type pressure sensor which we apply to read all the pressure or force we needed.

3.4 The measure of torque

The torque is a very important indicator during the bolt/nut tightening, it helps a lot to understand the working condition of the tightening process, and has a good value to realize the automation control and diagnostics. In order to measure the torque applied to the nut, various method can be adopted. The most common way is to use a torque meter.

Torque meter can be also a strain gauge based, the strain gauge is put inside some cylinder which is able to deform a little under torque, the torque range is match with the torque range in our application.

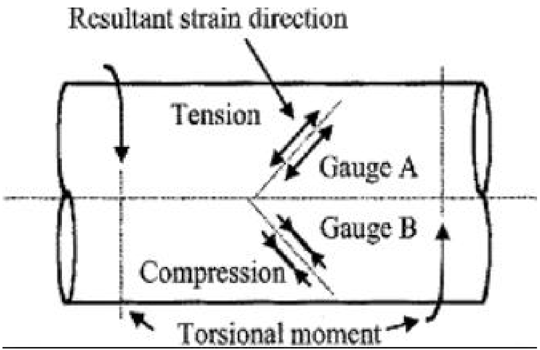

Figure 52. The position of strain gauge

Picture 52 shows the position of the strain gauge in order to measure a torque. The strain gauges are mounted inside a cylinder, the location is at middle of the length and at the axis, so to reduce the sudden change of dimension which will cause the deformation locally increasing. And from the material mechanicals, the shaft will in a resultant strain direction 45 degree to the horizontal line, so the strain gauges are put in-line with the direction of resultant strain. In the figure two strain gauge is put and under torque, one is in tension and another one is in compression.

And the remain part is the same as the pressure sensor introduced above, the strain gauges are connected to a external voltage source with bridge configuration. The results can be read in the same way.

The torque sensor can be firstly mounted inside the stem since the torque is applied to the stem. It will work if the stem will give enough deformation under torque. But I'm afraid that the stem is not the case. So there should be an additional cylinder which is more easy to deform under torque, the strain gauge is mounted inside with proper angle 45 degree, and the cylinder with one end connected to the propulsion system and the other end will connect to the stem.

And another problem is that the torque is an upstream torque. Since the torque applied to the nut is the real torque we want to measure, but it's very difficult to measure it directly at contact surface between pushing head and nut, so with the force balance, the torque applied at surface stem/propulsion system is in balance with the torque applied to the nut. The balance should also add some more items since when the torque is transmitted from propulsion system down to the nuts, there will be frictions in between every contact surface. And also, since when the stem going down, the nut end-stop will contact on the side of stem with a certain pressure, this will generate also additional dissipation. So some models should be build to simulate the dissipation and to correct the torque curve we got with those upstream torque sensor.

Another way to measure the torque could be an indirect way. This method can be used when the propulsion system in charging of provide the torque is an electric motor, so the in the circuit the voltage and current can be easily measured and so with their products, the power electric motor output is calculated. And then with a sensor measure the RPM, the torque value can be get by divide the power by angular speed. The angular speed can be get by using a photo resistance.

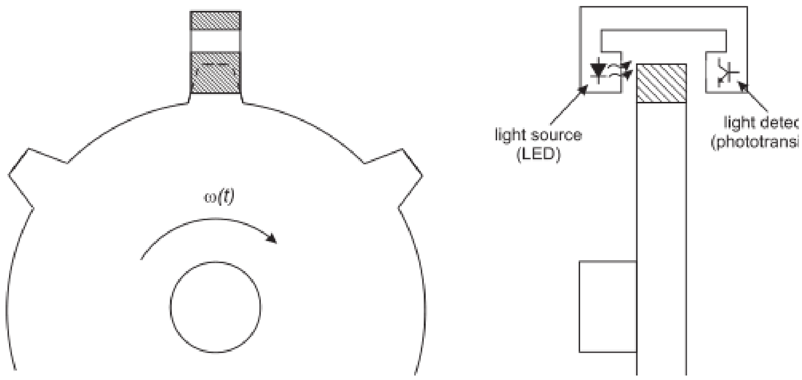

Figure 53. The optical sensor

The end of stem can be designed with shapes of extrusions, extrusions is uniformly distributed around the circle, and in one surfaces, there will be a LED always light and on the other surface a photo resistance is placed. The resistance will change it's resistance according to the light intensity it is exposed to. So when the stem(the circle) is turning, the photo resistance will periodically change it's resistance because it will periodically blocked from the light. So the related current result the sensor give will be some quasi square wave with specific frequency, the RPM can be get from the frequency and the current angular position can be get by counting the number of square wares.

And since the voltage and current measured are related to the battery output, it will also have some dissipations during the energy transform to the motor rotor. The first is that in the armature circuit, the battery internal resistance and the resistance of armature wires should be considered, and with some degree of dissipation in magnetic field so the actual power passing to the stator will be reduces. Also there will be frictions between moving parts inside the motor.

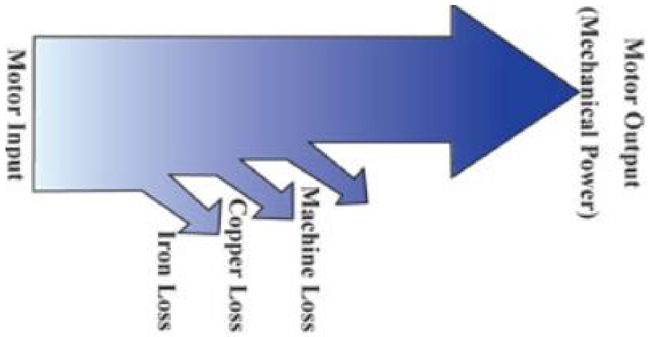

Figure 54. The power flow in a motor

The motor is supplied by electric power and output a mechanical power, the figure 54 shows the power flow from electric power to mechanical power. There are iron field relate to the generation of magnetic field, the copper loss due to the resistances of wires and the mechanical loss due to friction. So besides the models so simulate the loss during stem movement, additional models should be introduced for the loss inside the motor. And the result should be proper adjusted.

In between the two method, they share the same drawback in measuring the upstream torque. The indirect way is simple since the sensors needed are of very common and cheap types, the drawback is it will introduce additional inaccuracies and it need more time and power to do the calculation. And since it involves many sub sensors, the whole measurement system is more like to be a transducer, it's inaccuracy is multiplied by the inaccuracy of each sensor, which may lead to a no negligible result, this shows the transducer a higher instability compared to the torque meter. But the advantage related to many sub sensors is that it helps a lot to the diagnostic process, since we got more datum, we can judge the working condition through more aspects. And refer to the torque meter, it need an additional cylinder to connect between stem and propulsion system, it's a degree of inconvenient

3.5 Other datum

Some other datum can be measured in order to give information of the working condition together with information from other machine, such as some displacement of the moving parts, for example the sensor to measure the displacement of work piece to ensure the start time of the tightening machine, and also helps to transport work pieces to correct position.

Section 4: The control strategy

4.1 The timing to be defined

Preload is the most important thing we need to guarantee during the tightening process and also it is the target of this machine, the idea is to realize a more accurate control of the preload, it needs the knowledge both from propulsion system and from the sensors. The control of the propulsion system is realized through evaluation of sensor outputs and to define some important timing. Follow the procedure of the machine, there are some timing we need to define.

1. t_0 to put the nut on the nut feeding channel
2. t_a to start push the nut feeder
3. t_b to start to stop the nut feeder and then pull back the feeder
4. t_1 for the stem to going down
5. t_2 to rotate the stem
6. t_3 to start going up for the stem, hence the end of tightening

where the number 1 to 4 are related to the movement of the system and the remain t_3 is related to the control of preload.

4.2 The control of the former 4 timing

The former 5 timing can be controlled, or determined by one sensor. That is the sensor but between propulsion system and nut feeder to measure the pressure between nut feeder and propulsion system. And thanks to the force balance, this pressure should be the same as the pressure between nut feeder and the nuts.

In figure shows the pressure trace between nut and nut feeder, as mentioned in last paragraph, this curve can be get from the sensors put between nut feeder and propulsion system, and the shape can be get directly from the sensor output current, if the sensor is an analog sensor, or after a DAC, the digital analog convertor to convertor the digital signal to the related analog signal if the sensor is a digital sensor. Unfortunately I don’t got a pressure sensor on hand, so the trace is a theoretical one and in figure 55, the curve represent rough the trend of pressure changing while in reality, the would show many oscillations due to vibration during the movement and also show some smooth change not like in the figure. But the control strategy will not influence by those detailed changing, so can be evaluated by this approximate curve.

Figure 55. The pressure between nut and nut feeder

As shown in the figure 55, the vertical line presents the pressure and the horizontal line present the time. The blue curve, which is the pressure should be periodic during the whole life of using, and since we implement three dimensions of nuts, the curve will keep its shape, but with some heights or lengths changed if we pass from one nuts to another.

So firstly, the t_0, the starting time of a process, this timing is defined outside. It is the timing when the work piece is been put right under the stem, and this information is given by external system and sensors which not include here in my project, so we just treat it as the start point of a entire tightening process. So the nut has been put on the channel, since it still haven't reach the nut feeder, the pressure curve shows a horizontal line equal to the rest value.

And while the nut finishing its sliding and it fall and hit into the nut, this hitting process will generate a sudden increasing of pressure as shown in figure as the first changing. So the timing t_a which corresponding to the timing starting pushing nut feeder can be set as the time just when the pressure be back to the rest value. Of course there should be a short delay between t_a and the time when pressure firstly come to rest value again for two reasons. The first reason is that for the smaller nuts, it need some time to sliding to it's own depth and the second reason is that during that process there would be pressure oscillations, so the pressure may be oscillate around the rest value, reaching rest value only doesn't mean the steady state. So the delay is set to ensure that the nuts is stop and ready to go.

Then after t_a we can see a small rise of the pressure, this is due to the acceleration during movement, so the inertia makes this pressure, but since we won't experience a high acceleration, the pressure value is not far away from the rest value. Then when the nut reach the nut stop-end, due to the contact the pressure will sudden rise to a very high number, and if we don't stop the nut feeder, this pressure will tends to infinite until it damage the machine or the nut popping away. So a threshold value of pressure is hold, when this value is reached, the propulsion system stops. Then the pressure is hold on the threshold value, indicates the nut is already at its position. So t_b is determined, and t_b is also the time for the propulsion system to push nut guider core and nut guider sleeve going down since the nut is already there, so there will be a certain time for the guider to be in position while during this time the pressure level is keeping at the threshold value. Then after a defined interval t, the nut feeder start to going back. This t is defined to ensure the guider is in it's position during any condition.

And also at time t_b+t, thus the nut feeder starting to going back, this is the timing for stem to move. Up to now we define all the former 4 time. When the nut feeder is moving back, we can see the pressure is drop down dramatically cause it leaves the nut end-stop, and then fall to a certain value smaller than the rest value, this is because the acceleration in the back direction will make the sensors deform in opposite way, so the output diagram shows below the rest value. And we can see after a certain value, the pressure back to the rest value since the nut feeder have arrived the original position and stops their. Notice that the figure 55 ends shortly the nut feeder arrived its original position. In real time, the pressure curve will go on with rest value until and next bolt/nut is starting to be tighten.

And although the machine is working with three different dimensions of nut, the control of timing up to now is the same, since it is a quality control, the threshold is set to a proper value where all the nuts can be used, and it will not influence the results since the exactly is not important for the control of time mentioned in this section, the more important thing is the trend. And this threshold very should bigger than the possible oscillation pressure value near them in order to not be activated by oscillation.

4.2 The propulsion system

In order to control the rest time and to realize the preload setting, firstly we need to specify something on the propulsion system. Since during the tightening process, the pushing head turns and make the nut turn with it's self, and because of the rotation, the nut will go down follow the thread, if the pushing head didn't going down at same time with enough displacement, the nut and pushing head will separate and no torque transmit in between, and if the pushing head move down but with too much distance, the pushing head will push the nut hard against the thread, thus generate large, unnecessary friction. So for avoid the above two situations, the speed of translation and rotation should have some inner connection. The idea is to may this two velocity related through different ways.

Assume the thread have a diameter of D and the rotation speed of nut is w, every turn of nut will make it going down for the distance p, the pitch of the thread, so the translation speed is equal to p*w, where w has a unit of rev/s.

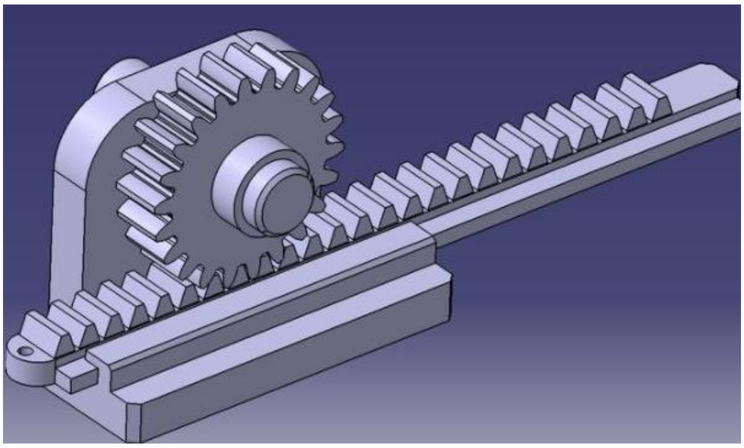

Figure 56. A possible configuration of mechanical transmission

One way is to mechanically connect them through some transmission for example the structure in figure 56, it related the rotation with the translation, and so after with this device, with some more gears or shafts to get the right axial direction, it can in charge of the rotation and translation through by using just one motor or one hydraulic system. And we can add a clutch to disengage the rotating part from the translation part to get the first downward movement without rotation. But the mechanical efficiency won't be high and the structure may occupy additional space.

So for efficiency and space saving consideration, the rotation and translation movement can be in charged by separated sub propulsion system, but these two system are controlled by computer to make them have a speed relation. So in this method ,two more sensors should be introduced to measure the individual speed to make a feed back control. The RPM sensor has been shortly introduced in section 3 by using optical sensors. And the translation speed can also be measured by optical sensor if we use a structure like in figure 56 to convert it to a rotation, the rotation speed sensed by optical sensor can be convert into linear speed.

4.3 The force analysis during tightening

Figure 57 shows a force analysis at the end of the assemble, and since the work pieces is applied under force F_p, it will give a reaction force of same value inverse direction to the nut, so the nut is pushed out to the right, this make nut contact tight with thread, more specific, every thread of nut will contact with the upper thread of bolt, so the bolt will give a reaction force to the left, nut is balance by this two force in vertical direction.

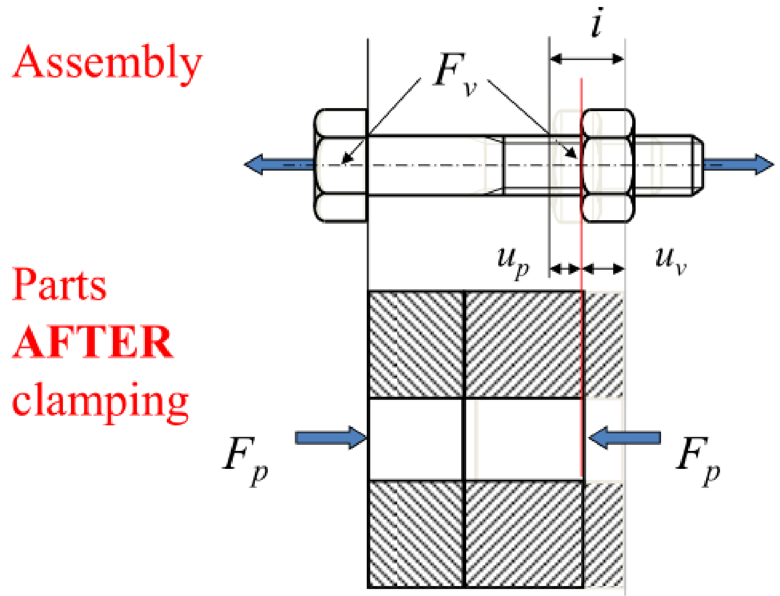

Figure 57. A force analysis for on external

Figure 58 is a force analysis of nut and it's direction is a little different. First of all, it is at the end of tightening, and the contact surface between nut and work piece is in the direction upward which is different from the direction we described in last paragraph. The pink one is the bolt and the blue one is one thread of nut. Since the nut turns counter-clockwise to moving up, the bolt will give a reaction force Fv upward, and since the support force between nut and bolt will always normal to the plane of thread, the support force N can be calculated from vertical force Fv and thread inclination angle a_m.

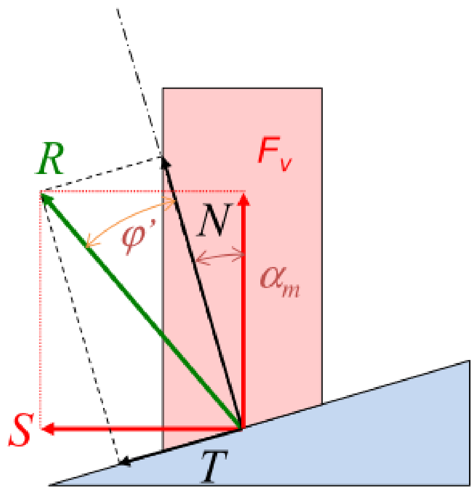

Figure 58. A detailed force analysis from internal

And since there also have a friction force along the thread plane and downward due to the support force, it can be calculated with the friction angle φ or the fiction coefficient f = tan(φ). With the support force and friction force, we can get the resultant force R, which have a vertical component Fv and a horizontal component produce a resistance torque. The torque is produced with force S with an arm if dm, the average thread diameter.

So the clamping torque is balanced by two torques, firstly one is the resistance torque calculated before, the second term is the friction between nut and work piece since these two parts are also contact tightly with force Fv. So introduce another friction coefficient f2, we calculate the friction force. But for the calculation of torque, we need to define the apply position of the friction, the effective diameter. The friction can be treated as a normally distribute on a annular plane with outer diameter equal to the internally tangent circle diameter of hexagon shape, and the inner diameter is the thread maximum diameter. The effect diameter is where the torque balanced at that diameter. After all, the total resistance torque can be calculated as:

$$\mathbf{M} = \frac{\mathbf{F_v}}{\mathbf{2}}(\mathbf{d_m}\tan(\mathbf{a_m} + \boldsymbol{\varphi}) + \mathbf{d_t f}) \quad \textbf{equation 8}$$

M: the resistance torque

Fv: the preload, the vertical force between nut and bolt ,also between nut and work piece

d_m: the average diameter of thread

a_m: the inclination angle of thread

φ: the friction angle between nut and bolt

d_t: the effective diameter of friction force between nut and work piece

f: the friction coefficient between nut and work piece

Since in our application, we need to control the preload, thus the vertical force Fv. There are two method we can measure the force Fv, the first one is to use a torque meter since the force Fv is direct link to the clamping torque through equation 8, and another way is to just measure the vertical force. Through force balance, we can measure the balance force of Fv in the upstream component such as pushing head.

And refer to the equation 8, it is applied when at the end process of tightening, and before the end, when the nut is just touched the bolt and start to clamping, the clamping torque can be calculation also using equation 8 by with some term change.

As mentioned before, the rotation and translation speed of stem are controlled so with one turn it will going down with a distance equal to the thread pitch just like the movement with nut so there will be no change of pressure between pushing head and nut during the tightening, since they are of same speed and nut is going down due to the profile of thread but not due to the pushing of pushing head. The constant pressure value is not so big and is because when the nut touches the bolt, it will hit and contact tightly with pushing head with a certain pressure, and it will maintain during the tightening process. So the vertical force is only the gravity force of the nut, substitute the Fv with gravity force of nut in equation 8 and we will get the torque at the start and middle stage of tightening.

4.4 The control with torque meter

In order to define the end of tightening where the desired preload is reached, the torque meter is used.

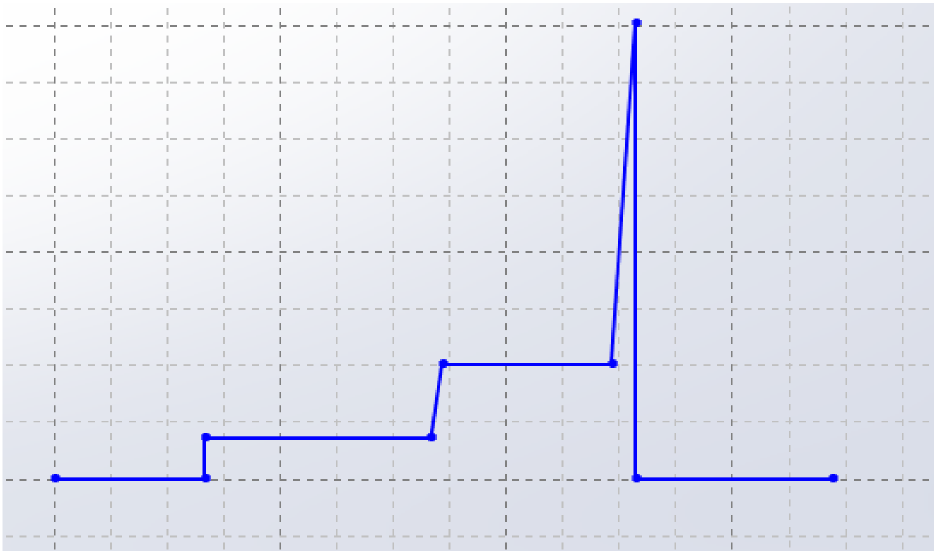

Figure 59. The torque cuvee

The figure is also a figure shows roughly the shape trend of torque, and one thing need to be noticed that the starting point of this figure is not the starting point t_0 but after a certain value, since in this application, the stem is not rotate at beginning, and before it's rotation, of course the torque will be 0, or some low value correspond to the friction. And since this figure is used to control the preload, it need more accuracy than the pressure curve we used in last section, so some correction should be down.

And at t_2, the stem is start to rotation and the torque is rise to a certain value, this value is low cause the resistant torque in low and we only need small torque to guarantee the speed. And the way to determine the time t_2 will be shortly introduced later. And after the period of almost constant torque, the torque is increasing cause the nut have in contact with bolt, and the nut is pushed against with bolt by pushing head, so with equation 8, we can calculate the torque. The vertical force to be used in this equation is the sum of the gravity of nut and the contact force between nut and bolt which is come from some simulation and models.

Then during the turning along the bolt, as analysis before, the contact force will keep same because the nut and pushing head will have same linear velocity, so the clamping torque needed will keep the same, the torque curve will be horizontal. Then when the nut start to contact with the work piece, the vertical force will increasing due to the contact, and will rise with a very high slope, what we need to do is to stop the rotation when the torque value is equal to the value calculated from the desired preload. And since the rotation speed and translation speed are related, the pushing head will stop, nor turning, nor going down, the tightening phase is end.

Then almost the same time when we reach the maximum torque, the propulsion system is control to going up, without rotation, so the torque will be equal to 0, until the next bolt/nut is start to be tighten. And noticed that the threshold of torque is calculate from desired preload which is changing casing by casing, nuts by nuts, so every time a nut come in, the setting of threshold should be changed to adequate value.

And up to now, with this torque meter we put all the time under control but the t_2 where the stem start to turn. Since it is the start point of the torque curve, we can't do any control of this value of the torque curve, the only way is to put another sensor dedicated to the control of t_2.

There are basically two types of sensor we can use, the first one is the simple displacement sensor to measure the position of pushing head, the sensor can be a optical one and be put at some few distance below the rest position of bottom of nut end-stop. And when the pushing head is measured passing the sensor, light will be blocked and curve generated, and then the curved change due to this, this is the t_2 determined to start rotation of stem. But since the nut is sit on the flexible part of nut guider core, and for different dimension of nut, it's height from ground is not the same, so the position of sensor is set to be the lowest value of the height, when all the possible nut position is above it. So we can guarantee that all the nuts can be fit perfectly into pushing head due to the predefined direction of both. And actually, the sensor could be anywhere between the bolt and end of the nut guider core.

Another way is to put a sensor between the nut guider sleeve and it's end-stop inside the middle hole of the stem, and when the pushing head fits the nut, it will need to push it passing the nut guider core, and nut guider core is stick to the sleeve cause it reaches the end-stop inside sleeve, so the force will be transmit to the surface between nut guider sleeve and the stem.

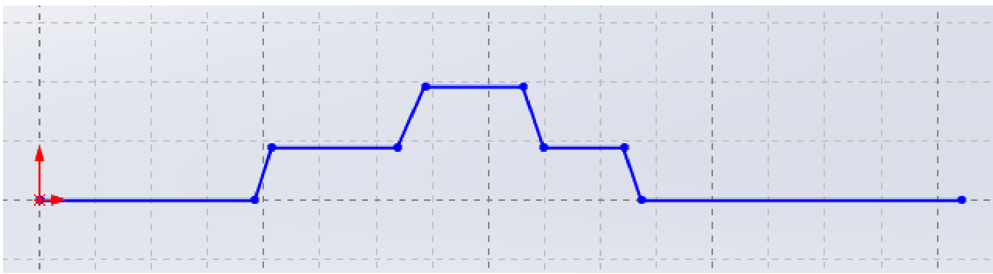

Figure 60. The related pressure curve

And since this pressure is exist only when nut guider sleeve contact the sleeve, so at the start and when they contact, there will be a certain value due to the gravity. And the middle increasing of pressure is due to the fitting process, and the time t_2 can be set as any value then the pressure is drop after the maximum value. But since during the process the stem is also move, so the real curve may shows different shape and can't be used to control the time.

So another pressure with more stability can be introduced. This sensor can be put inside the flexible part of guider core.

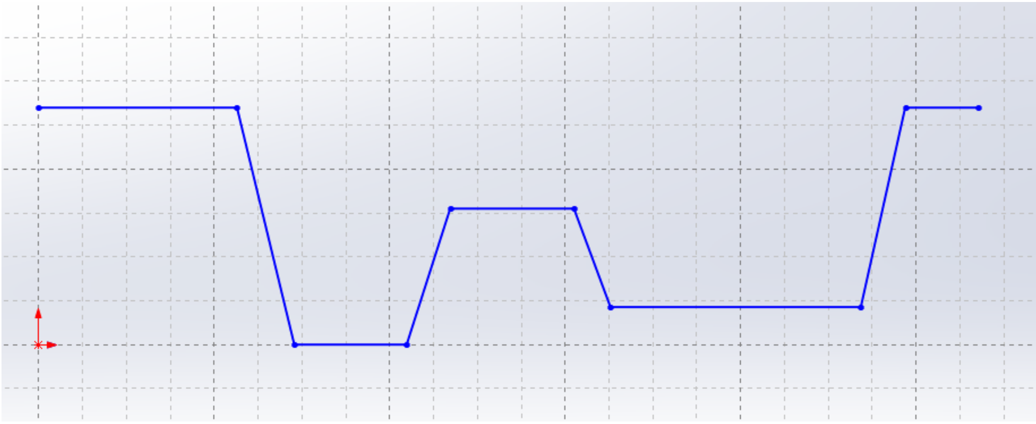

Figure 61. Pressure between flexible part

Since at the start and end of process, the flexible part is convergent to be put inside the nut guider sleeve, so the pressure will be high. And this could be an durability problem since this senor is at mostly time working under high pressure condition. And after the flexible part contact with nut, the pressure goes to 0, cause the gravity of nut is too small, the flexible part are extend to its maximum shape. And when the pushing head comes it convergent the flexible part again, so the pressure is increasing but to a lower value than it's initial value. This is because the hole of nut have a greater diameter than the diameter of nut guider sleeve mid hole, so the flexible part are compressed to a less degree. And then the pressure is fall to a value higher than zero, cause not the stem is moving down, the flexible part is a little convergent to be inside the mid hole of stem. and finally, the core moving up to it's original position and the pressure goes to it's maximum again.

4.5 The control through pressure

With torque meter, we can realize the accuracy control of preload, but as introduced above, it needs dedicated additional sensor for the determination of t_2. But if we put a pressure sensor between the pushing head and stem, we realize the control of both t_2 and preload with only one sensor.

The idea is through the force balance. Since at the end of tightening, in vertical direction, the nut is under two force, the work piece pushes it upward and the bolt pushes it downward, so the clamping torque is calculated as equation, the result is big since the vertical force is very big so the resultant force and friction force between nut and work piece.

The idea is if we give a downward force on nut by the pushing head, and it's value is exactly equal to the vertical force work piece gives to the nut, the nut is balanced by this two force, which means there is no force between nut and so no support force and friction force, the first term in equation 8 disappear. And the force pushing head gives to the nut is exactly the force act on the sensors, so it means the sensor is directly measure the preload.

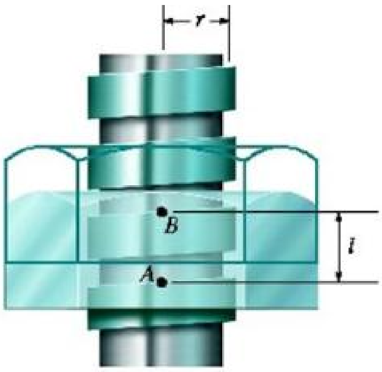

Figure 62. The bolt and nut

But how do we pushing the nut with exactly the same force as the preload. The way is to change a bit the prolusion system control strategy. It still use the relation $v = w*p$ described before but with some change and the speed relation is realize by the computers. W is the rotation speed and it is also the vertical speed of nut, and during the tightening, if the stem is propulsion at a higher speed, or it tends to increasing it's speed higher than the pre related value w*p, the stem will contact tightly against the nut, although the stem will still move as the pre related value due to the profile of thread, but it can generate a pressure between nut and pushing head, and this is exactly what we want. And besides this, the rotation of stem is also under controlled, the torque is controlled as a constant value. This value is calculated from equation 8 with Fv equals to the desired preload and neglect the second term since nut is not pressure to the bolt.

And if we feed the nut with this constant torque, during the start and middle phase of tightening, the nut rotation speed is increasing since the resistant torque is much smaller than the driving torque. And during this phase, the speed of translation is set to the related value p*w in order to avoid the high pressure between nut and pushing head which will results in higher resistance torque. And thing goes well until the nut reach the work piece. When reaching, consider there is almost 0 pressure between nut and pushing head, the resistant torque is still follow the equation 8 and as the Fv increasing, the resistant torque will increase and exceed the constant driving torque, the rotation speed start to go down, so when we notice that the rotation speed is going down, we realize that the work piece is contact tightly with the nut, the preload form, it is the time we can increasing the translation speed beyond the pre related value, as a result, the pressure between the pushing head and nut will starting to progressively increasing. And at the end, this pressure will equal to the preload and form a equilibrium in vertical direction, and also, the resistance is equal to the driving torque, the speed of rotation is 0, so also the translation speed is 0, the tightening finish.

And the pressure signal is shown is next page. At the beginning the pressure is 0 thanks to the structure to balance the gravity, or the pressure sensor will undergo a tension and shows negative pressure. And after a certain, the pressure rise, this is due to the contact of pushing head and nut upon the flexible part of nut guider, so after the process, the pressure fall back to 0, this is the time to starting rotate, so the time t_2 is set. Then after a short time we can see that the pressure is rise due to the contact of nut and bolt which will form a small contact pressure between nut and pushing head. Then the pressure keep constant until the nut reaches the work piece. Up to now the speed control are the same as in torque based control strategy.

Figure 63. The pressure curve

And when the rotation of speed is start to decrease and it can be observe from the derivative of rotation speed, the translate speed is set to corresponding to the value of Δt before. So, when dw/dt is negative, v(t) = w(t-Δt), since the w is decreasing, v(t) will always higher than the pre related value w(t)*p. And from now on, the pressure is increasing and is comparable to the preload.

At the end, the pressure is equal to the preload and when the pressure reach the desired value, we stop the driving torque and start to going up. Just for verification, and consider the extreme condition. The nut is stopped and the pressure start to increase, this increasing with reduce the resistant torque, since the driving torque is still there the nut speed in increased and then reduce, it means the control will further increasing the pressure, so the last step repeat, and when the pressure is equal to the desired preload, the nut will stop and don't rotate. And since this happens in a relative short time, it's feasibility need to be verified.

Section 5: Other usage

The information we get through variable sensors, from all the system, they can exchange within different machines, so to improve the whole working process. The information form sensors outside from this machine is also important to guarantee the normal working of the tightening machine. The most important one is the position sensor to measure the position of work piece. Since the pushing head and stem can only doing up and down translation based on this design, the working position is fixed can should be strictly followed by every pair of work pieces, if not, the tightening process will go wrong and more sever the machine would be damaged. Also this sensor is in charging of determine the time t_0 to start the process as mentioned in last section, also, there could be some sensors to give information about the situation of material flow, such as some type of nuts is about to used out, some type of bolt is not ready and so on, there will influence the product flow rate and the normal high efficiency operation of all the system.

And another very important information is the type of nuts, this should be the ingoing information with the work piece. Since the work pieces are connected to the internet of things through coding, marking, RFID signals, the ECU, electronic control unit should recognition the type of nut and also bolt going to mount, and prepare the related component at the feeding channel, this exchange of information and deal with data should be with less delay since it will make all the machine to wait for the information.

And the information generated and sensed inside the machine, will not only benefit the control strategy, it will be very helpful and meaningful during the diagnostics process, since the curves should show some common laws about it's shape based on the theoretical one, even though the real one will have more oscillation and smooth changing and value compensation, if there exist some difference or some strange part it can be see as something is going wrong. We can pre define some cases we think is not good, can trace the reason, so we can writing coding for these conditions, if during the process the situation is detected, related correction action can be take, these actions can be treat the products as defects and transport it to some specific place rather than let it go through all the next process and become a final product with defects. Also if the condition if really sever, the whole product line should be shut off, and people or robots should be sent to repair or maintain. The two correction is taken based on the severity, so the percentage of the difference between the curves detected and the theoretical one.

5.1 diagnostics

In diagnostics, two types of abnormality can be found, one is the abnormality of data value, the values shows zero when it is supposed to be a certain value, or it is much lower/lager than the predicted value. Another is the changing of timing, such as the rise of measured value takes place after too much time than what we expected. Usually the two types are not take place at same time, since the probability of such events is not so big, in most of the time, the machine is working properly and the data measured shows good. So the diagnostics process is always on even if we have already found something wrong, there could be two or more events exist and we need to compare to diagnostic to find them all.

Theoretically every curve mentioned in section 4 to be used to control is the inputs for diagnostics, but since there are infinite types of abnormality, I only list some important and usual ones with those most important curves.

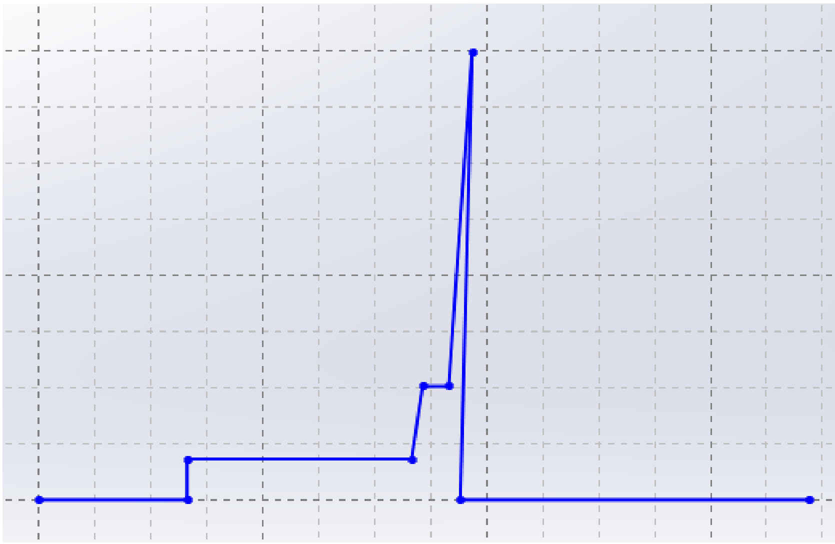

Figure 64. A abnormal curve of torque

Take the torque curve as example, the figure shows a abnormal curve of torque curve where the second horizontal period is very short which the period indicates the period where nut matches the bolt, and moving closer to the work piece along bolt. Since when the torque rise after the previous constant small value, the timing is been marked as the start time of tightening process, and the almost vertical one is the timing the process is over, normally it takes a certain time for the nut to turning and moving along the bolt to work piece, but if the face of bolt and nut is not perfect match when it reaches bolt the period will be extremely reduce because of the strong reaction force come from the non match profile. The reason can be the inclination of nut then before it reach the bolt, or there is some teeth missing on bolt, so when the nut move to those area, it start to inclined due to the unbalanced force. And also an important reason is the bolt and nut is not concentric. And last but not least reason, the nut is not the proper dimension. Above are all the reasons and some can be identified by the position of the maximum torque value. If this value is still have a certain distance from the first touch of nut and bolt, it is due to the missing teeth and in the rest conditions, the maximum torque value is about to appear almost immediately after the first touch of bolt and nut. And for the first case, the identification should be care fore. Since every nut have a little difference in dimension, not only on the diameter and shape of thread, also the number of turns from the head to the end, so there should be a interview of time during which the nut and bolt could be work in a normal range. So the threshold value is set according to the lower limit of the interview, if in the torque curve, the second horizontal is shorter than the threshold, the above mentioned casing is taken place and related correction action should be done. Since the nut is almost at the end of bolt, it need to be take away instead of letting it go with nuts. In some applications the stem is moving with different speed nut by nut, the time period should be convert with the speed curve to get the displacement nut move along the bolt, and this result would be the most accuracy one, since every type of nut shows a certain range of distance from head to end, and it can be the indicator to set the limit of normal operation range.

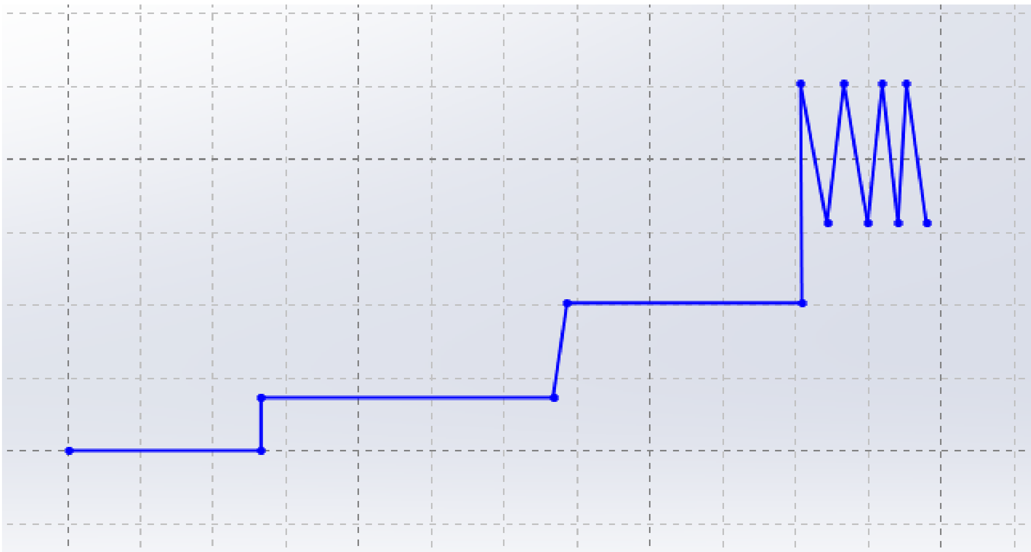

Figure 65. Another abnormal torque curve

Opposite to the too short contact time or distance, the figure shows another situation that is the too long contact time or distance. This is due to the missing of teeth of thread on nut or the thread be close to the head, and those missing didn't cause the inclination of nut so it would not show a shorter time like last paragraph. Due to the big vertical force between nut the work piece, and the force to balance it is not enough due to the missing teeth, the nut will reciprocating with a small distance at the end of the stroke, and the preload will never reach the desire value since once it reach it, it will be pushed out under unbalanced force. So the final part will show a strong vibration. So if the too long distance is measured, the stem should stop and going up to leave the nut in the last position with lower preload than what we would. Then the nut and bolt should be checked and replaced, the work piece should again do the tightening process.

And remain some extreme condition that the torque is almost keep constant as the value of first level of horizontal line, this could be due to the missing of nut or bolt, so there is no tightening, no torque will be measured. Also, if the torque keep constant as a high value, some parts may stick and the additional torque is measured to keep the rotation.

Then also there could be many possibilities with the pressure curve.

Figure 66. The theoretical curve of contact pressure

In figure 66, the second part is also refer to the contact period of nut and bolt, and the two situation like in torque curve can also be taken place here. The reasons and results are the same. If the maximum pressure occurs very close to the first touch point and the maximum pressure occur before the reasonable range of time, it should be consider something is wrong, and related correct action need to be done.

But in this case, the too long contact period due to missing teeth would not happen, since when nut touches work piece the pushing head is pushing the nut against the work piece by increasing the speed over the nut speed, so the vertical force comes from the work piece will totally balanced by the force come from pushing head, as a consequence, before the end we will not notice if there is missing teeth. The result is different after the stem starting to going up. As shown in figure 67, the pressure will not fall back to zero like the normal one, but will reduce gradual because when the pushing head stop to giving force to nut, the all vertical force will applied to the bolt and nut contact surface, but with missing teeth it can't handle so high pressure, the nut would be pushed against the nut, so the pressure senor measure a value still high, only after the pushing head is not contact with the nut, the force is going to zero. So the detect could be determined by a small time interval Δt, we measure the pressure at the time Δt after the stem starting to going up, and if this pressure is higher than zero, the missing teeth situation is determined. Of course this Δt value should be choose carefully, if it is too big, of course the related pressure value will go to 0 cause the pushing head is already leave the nut. But if this value is too small, maybe even in normal condition the pressure is not reaches zero, so it should also based on statistic result to give a suggestion where the normal situation will end.

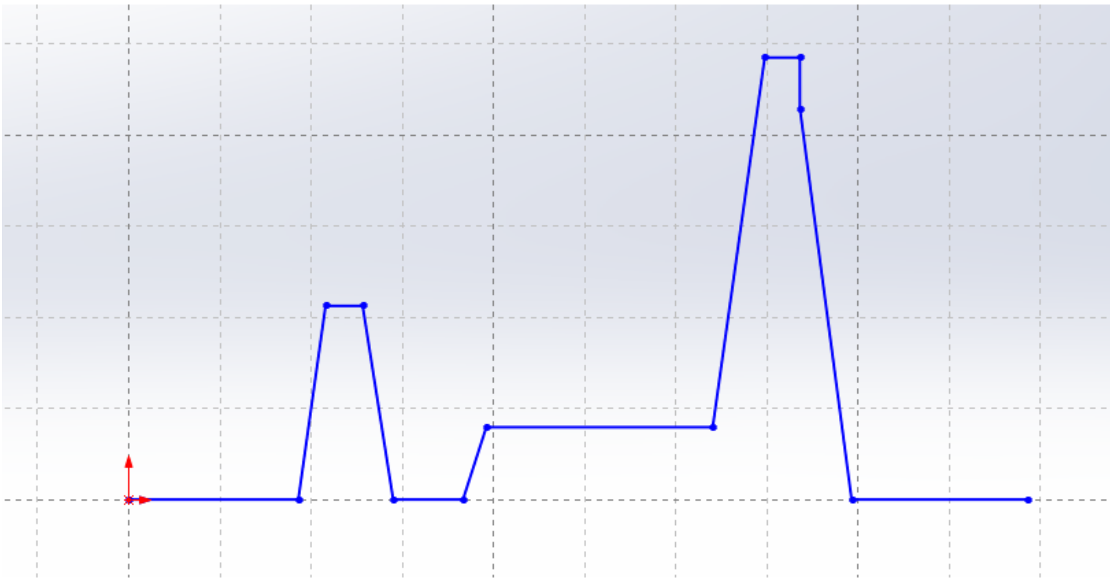

Figure 67. The missing teeth result

It is obvious that the wrong operation will take place due to many reasons and show many different results, even though we try our best to pre set all the abnormal condition, we can't foresee everything. This could be solved by the machine learning ability in Industry 4.0. The machine will collect information about the abnormal condition and the related solution, and the next time same thing happy, it will have a guide to follow, but still this technology is under development, so the pre set of all the possible abnormal condition is very important.

5.2 Collaboration with whole system and other machines

With the data we measure inside the tightening machine, the machine ECU can also do some analysis and calculation as an output which would benefit the whole production process.

One possible result is the calculation of product flow rate. The flow rate is more like a prediction of the speed to complete the next operation. And it can be read direct from the torque curve or the pressure curve, since we have already defined the start point and end point of the whole process, the in between time is the time we need to finish one operation, so the flow rate would be 1 per specific time. Since we can calculate the time only when the operation is done, the flow rate is more like a prediction of next one if we keep same condition of the machine. Also in our case, the three dimension of nut will take different time, a weighting average can be calculate by the product of time need by each dimension of nut and the number percentage one dimension occupied so far. This average flow rate can be compare with the flow rate with all the other machine in the same production line. Since the final product flow rate is decided by the smallest one among the machines, if the tightening machine have a higher flow rate, it can be reduce the operate speed by reduce the translation speed of stem for example, this can save energy without influence the whole process. And on the contrary if the calculated one is much smaller and speed up should be taken to catch up other machines.

And also based on this flow rate, some change of configuration can be used. If the needed flow rate is much bigger than the current one, it should be add one more machine and if the flow rate is much higher than needed one, some machine can be disengaged from the production line, also this can be applied to all the other machine on the production line.

It can be seen that only one product flow rate can be of many usage, many other related quantities or information can be generated and exchanged so the whole system is working in smart way.

Section 6: Software and experiments

In order to realize the control and do some experiments to see will the machine work and use sensors to check if the real curves match the theoretical one, it is necessary to have the machine structure prototype, the sensors and relative software in charge of the control. But unfortunately, due to the limitation of time and money, I can’t get such a prototype, so the experiments can’t be carried out.

But about the software and related hardware, professor give a suggestion to check if it is possible with MECT starter kit. And it turns out to be feasible to use MECT starter kit, together with correct sensors, it is possible to realizes of the tightening machine and also to do some computations ,analysis and also it is possible to display some result we are interested in with the HMI monitor equipped with MECT starter kit. But since we don’t have the prototype of machine, such control is not going to take on, but in this section I will introduce my steps to get familiar with the MECT starter kit and to execute some exercise with it. Even though the real control is complex, it is composed by some simple exercises, with the execute of some specific exercises, we can check if MECT starter kit work with sensors and is it possible to realize some control.

6.1 The MECT starter kit

MECT starter kit is a product of company MECT, and is mainly be applied in automation field which is the base of Industry 4.0, so it become our choice to make those exercises.

Figure 68. The MECT starter kit

The MECT starter kit is mainly composed of a HMI monitor which type is TPAC 1007. This monitor is capable to display graphics and it can also realize some interaction with user such as push a button or insert some numbers or check the history and give alarms. And another important part is the STK board in charging of the management of inputs and outputs with Modbus RTU. There is a connection cable to connect the STK board and the TPAC 1007, and the power is connected at STK board. And then with a LAN cable to connect the TPAC to the computer. Is this way, we have the STK board, the TPAC 1007 and the PC all connected.

So the function is able to doing PLC and HMI process on the computer, where the PLC inputs and outputs are coming from the STK board, with proper coding, we can get the desired result to analysis, to computer, and to control. And also we can design the interaction interface on PC with graphs, buttons, LEDs and so on, this interface can be transferred to the TPAC 1007 and be displayed on the monitor, we can directly touched the monitor to see what we want, and also can do some simple control. And it is possible to transfer some files contains data in proper form to TPAC so we can read then and use then on the interaction interface. And it is also to connect the TPAC and PC through WIFI, so they don't necessary to be put in the same room, with dedicated VNC mode, it is possible to realize remote control.

The coding and design phase in done on PC by MECT suit software. It include the software called QT creator which is capable of doing HMI applications. Firstly, it can define some global variables which is share also with the PLC software, and it can use this variables together with the internal PLC variables to generate the interested interface to display the results. And with the proper design of interface, we can transfer it to TPAC 1007 through the software, thus the HMI is done. Also, it is possible to write some coding in the QT creator, coding can be written in c++, and the results can be shown. But usually the coding process is in the PLC software, the MECT control which can be directly open inside the QT creator. And the PLC software, we can write codes to realize control, and also can display some result on the STK board.

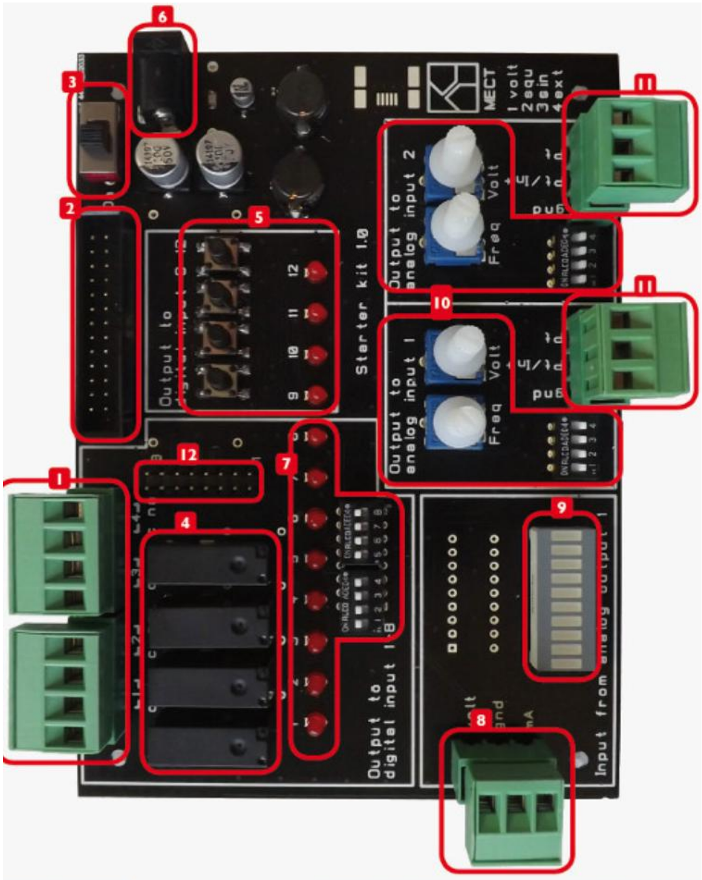

Figure 69. The STK board

Figure 69 shows the detail of the STK board on which we see many inputs and outputs port. It is divided into 12 parts. Particularly number 1 is the ports connect to the external digital inputs. But this STK board can also generate digital inputs by it's own, in area number 7 there are 8 lights with their switches, this eights is the eight digital inputs, by turn on or off it, it will generate the related 1 or 0 signals and is stored in related internal variable in PLC software, and we can directly use them in the software. And more of this, this eight lights can be also function as indications of eight digital inputs. If the related PLC variable is 1, without the turning of switch, the light is turn on cause it means the digital signal 1. The configuration of these lights can be modified in the software with the internal variable PLC_DigDir_1, the PLC stands for it's the internal variable of PLC software and is already defined with some properties, the Dig means it's in the digital region and Dir is the shorten as direction, since this variable control if the lights work as input or output. The last number can be vary from 1 to 8 and is the lights it refer to. If the variable value is set to be 1, then the light is working as an output, on the opposite set as 0, it is an input. No other value can be assign to this variable, since it's type is BOOL which can be only 0 or 1, or another word true or false.

Then in region 8 we have the analogue output and in area 11 we connect to the analogue input.

6.2 Exercise of counter

The first exercise is to follow a rough tutorial from the company to firstly get familiar of both HMI and PLC software, and secondly to make a counter to indicate the PLC circles. Before start the exercise, some preparation should be done. First is the TPLC 1007 is connect to the PC through LAN cable, and it is necessary to adjust the PC IP address adequate to the TPLC 1007 one so they can inter connect each other.

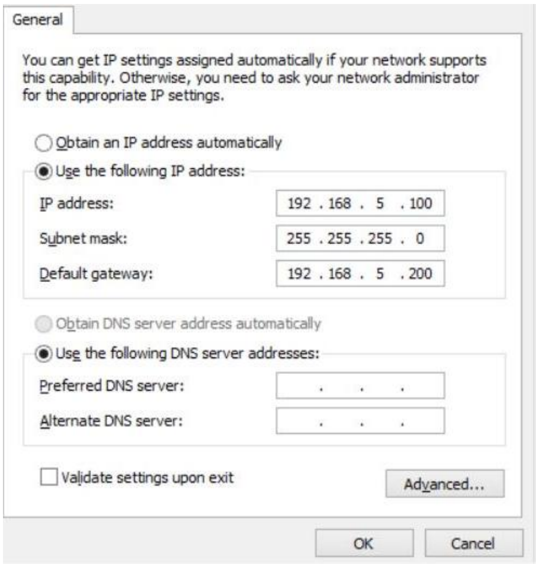

Figure 70. The setting for the internet adaptor

The way is to adjust the properties of internet adaptor, in the property of TCP/IPv4, the IP address is set to be 192.168.5.100 and the subnet mask is set to be 255.255.255.0 because the default IP address of the panel TPAC 1007 is 195.168.5.211, we only need to set the fourth number different from the panel, then the job is done. And then we can check if the connection of TPAC 1007 and PC is work, the way is to go to the toolbar and find the button 'tools', inside 'tools', there is a 'option', click on it, you can test the connection. And if the connection is correct, the below result will show. Only after the successful connection we can display the interface on TPAC 1007.

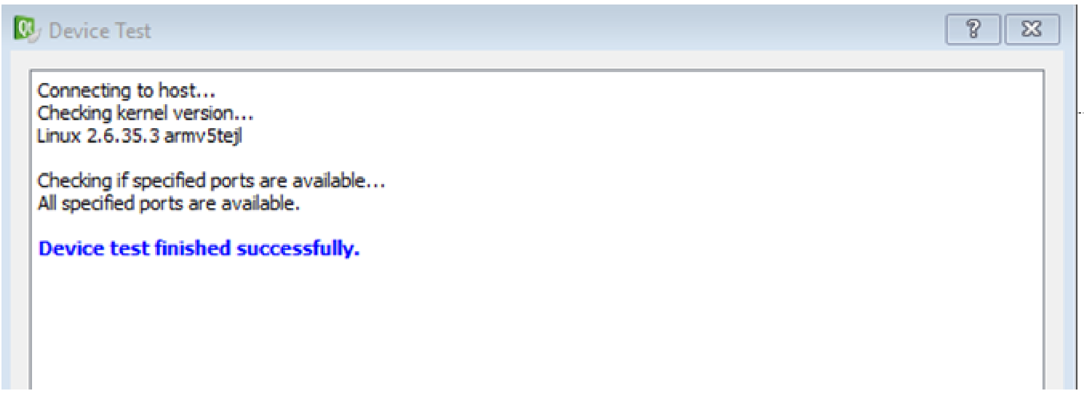

Figure 71. Successful connection

Then follow the exercise, the first thing is to define some global variables in QT creator so that we can use them. The define of variable is on crosstable.

	Priority	Update	Var.Name	Type	Decimal	Protocol	IP Address	Port	Node ID	Register	Bloc
193	1	P	Con_TPLC_In_An_1	INT	0	RTU		0	1	40	193
194	1	P	Con_TPLC_In_An_2	INT	0	RTU		0	1	41	193
195	1	P	TPLC_IN_AN_1	INT	1	RTU		0	1	42	193
196	1	S	TPLC_IN_AN_2	INT	1	RTU		0	1	43	193
197	1	P	Con_TPLC_OU_DI_1	BYTE_BIT	1	RTU		0	1	44	193
198	1	P	Con_TPLC_OU_DI_2	BYTE_BIT	2	RTU		0	1	44	193
199	1	P	Con_TPLC_IN_DI_1	BYTE_BIT	3	RTU		0	1	44	193
200	1	P	Con_TPLC_IN_DI_2	BYTE_BIT	4	RTU		0	1	44	193
201	1	P	TPLC_IN_3	BYTE_BIT	3	RTU		0	1	45	193
202	1	P	TPLC_IN_4	BYTE_BIT	4	RTU		0	1	45	193
203	1	H	TPLC_OUT_1	BYTE_BIT	1	RTU		0	1	46	203

Figure 72. The crosstable

The crosstable contain all the variable related to HMI and PLC, and the first column is the row number, from number 5390 to 5472 are all the internal variables for PLC just like the PLC_DigDir_1, and all these variables have name with PLC. On the contrary from row 193 to 499 is the space for us to define the global variables. And it can be seen we named them with TPLC to notice that they are global variables. And the variable are defined with some properties which almost all can be seen from the first line. The most important properties are the type, protocol and the register. The register is the number of registers of Modbus node according to I/O to use, so we need check what the value it is before we define the variable. The 'update' column defines how it change the data so how to update the data with TPAC 1007, especially the H type means it only updated if this variables is shown on the current page, and also if we want to update it, we need to write some specific codes in QT creator to activate this function. Then the P type is shown means it is always allow to update. And further more, there is another property doesn't appear in the figure, some variable are read only and some can both read and write.

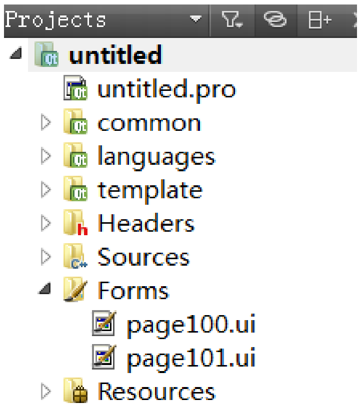

Figure 73. The project tree

The second step is to built pages and design what it is looking like. The pages will display on the TPAC 1007 panel. In the project three, we see all the component belong to our HMI application, also the pages, so double click the page under 'forms' folder and we can start to design it. On the toolbar there is a group called ATCM plugin, it contains all the elements we will need to interact, the LED, the graph, the bottom, the label, and by drag it into the page, we built the same symbol on page, and by clink the object, we can define the properties of them. The most important thing is to connect every symbol with the variables we want to display.

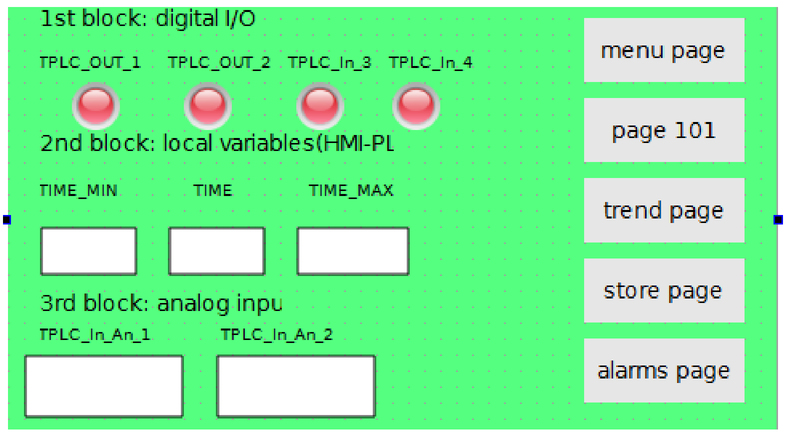

Figure 74. The designed page

The figure is the page designed, it composed four LEDs which individual to four digital signals, if the signal is of value 1, the LED will turn on. And below there are five labels each corresponding to an analogue value, and it's value will be displayed inside the label. Finally on the right there are five bottoms which if we clink them on the TPAC 1007 panel, it will turns to an pre set page such as store page where we can see the history results, the alarms page where we can see the alarms.

We can still adjust and design many things on other area of QT creator, but in this exercise we don't go deep through them. The next step is to build and run the project.

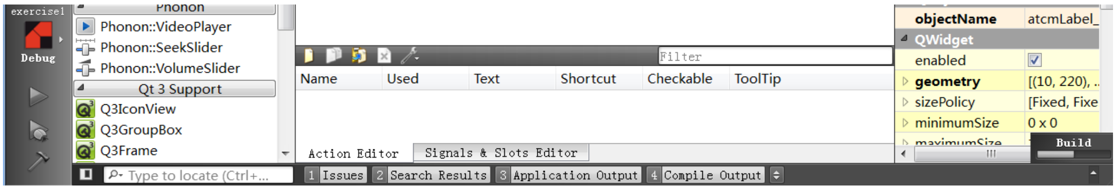

Figure 75. Build and run

And on the left bottom side, the hammer shape button is the 'build' button, with a click the project is start to build and the progress bar appear in right bottom side, when it turns green, the build process is done and click the triangle button upon the hammer, the panel build the same page as we design. Then we can go to the PLC software to write the coding relate to the counter in this exercise.

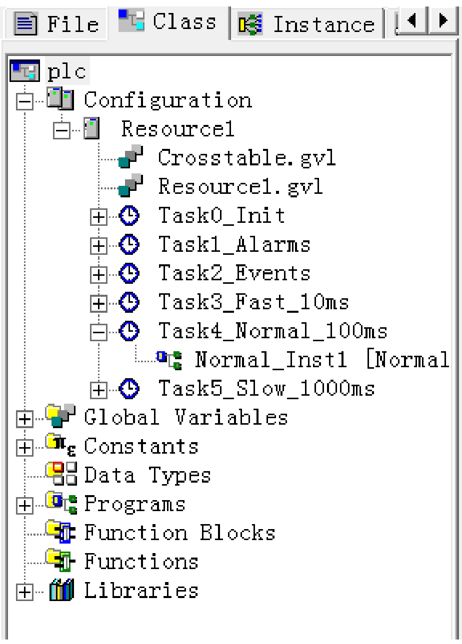

Figure 76. The projection three of PLC software

On the left of software we see this project tree, and there are two important content. The first is the global variables, inside it we can see all the variables we defined in QT creator and the internal variables, if you don't sure whether the variable you need should be re-defined, you can go through the global variables group and if the variable exists, it can be directly used. Another important group is the task 4, which is define as the normal task, the PLC software will circles every 100ms like it writes. Click on the normal task and we start to write codes.

```
PROGRAM Normal
#import "Crosstable.gvl"
#import "Resource1.gvl"
VAR

END_VAR


;

END_PROGRAM
```

Figure 77. The default area of coding

In the default area of coding, we can see the import of two files, one is relate to the crosstable and it contains all the variables, the defined one and the internal one. And between the row 'VAR' and 'END_VAR' is where we define some intermediated variables for computation, and between 'End_VAR' and 'END_PROGRAM' is where we write the main coding. Noticed that this program is already a loop function since it is be executed every 100ms.

```
PROGRAM Normal
#import "Crosstable.gvl"
#import "Resource1.gvl"
VAR
    value : INT;
    counter : INT := 0;
    period: INT := 10;
END_VAR
    counter := (counter + 1) mod 10000;
    if (counter mod period = 0) then
        value := (counter / period) mod 2;
    TPLC_OUT_1 := INT_TO_BOOL(value);
end_if;

;

END_PROGRAM
```

Figure 78. The codes

Figure shows all the codes to counter the PLC cycles. First we define some useful variables. The 'period' is defined as 10 since every 10 times of circles is 1 second, so we make a counter every second. The sign ':=' is used to assign a value, but it's not the c++ coding. And then every time we execute this normal task ,we add 1 to the previous 'counter' value, and we reset it every 10000 times, since the ‘mod’ stands for the calculation of reminder of the front value divide the behind value. And then the following code is to set the ‘value’ to change it’s value every 10 times of the circle, so one second, and since ‘value’ is a reminder, it can only be 1 or 0, with the function ‘INT_TO_BOOL’, we can assign the value of ‘value’ which is a integer to the TPLC_OUT_1 which is take as TRUE when assigned as 1 and FALSE when assigned as 0. So, the coding are trying to make the digital variable TPLC_OUT_1 every one second. And since this variable TPLC_OUT_1 is connected to the first LED in the pages, it is expected that it will turn on and off the LED every second.

Press F7 to build the project and to see if there is any errors or warnings, and then after assign the target as TPAC 1007 panel, we can download the coding to panel and start executing. But the result is not desirable since the first LED is always off. So some change is done to see what’s wrong.

```
PROGRAM Normal
#import "Crosstable.gvl"
#import "Resource1.gvl"
VAR
    value : INT;
    counter : INT := 0;
    period: INT := 10;
END_VAR
    counter := (counter + 1) mod 10000;
    if (counter mod period = 0) then
        value := (counter / period) mod 2;
    TPLC_OUT_1 := INT_TO_BOOL(value)    ;
    PLC_DigOut_1 :=TPLC_OUT_1;
end_if;

;

END_PROGRAM
```

Figure 79. An adjusted coding

There is only one additional line, no more coding. Is to assign the value of TPLC_OUT_1, which is a global variable we defined in QT creator to PLC_DigOut_1, a internal variable of the PLC software itself . Run the coding something strange has happen.

Variable / Expression	Type	Value	Time	Quality	Format
TPAC.Resource1.Normal_Inst1.counter	INT	317		Good:	
TPAC.Resource1.TPLC_Out_1	BOOL	False		Good:	
TPAC.Resource1.PLC_DigOut_1	BOOL	True		Good:	

Watch 1

Figure 80. The watch bar

Figure 80 is the watch bar of PLC software and it can show the value of each variable during the execute of coding, circle by circle. And three variables have been dragged into the watch bar, the 'counter', and the two outputs. As the execution going on circle by circle, it can been observed that the number 'counter' is keep increasing as expected, ten every one second, and it has already reach 317 in the figure. But on the below, the two outputs shows different value, even though they are interconnected by assignment. And it shows the TPLC value keep false all the same which matches the results we got last time, the light will never go on. But the PLC value is actually changing as we want, it varies.

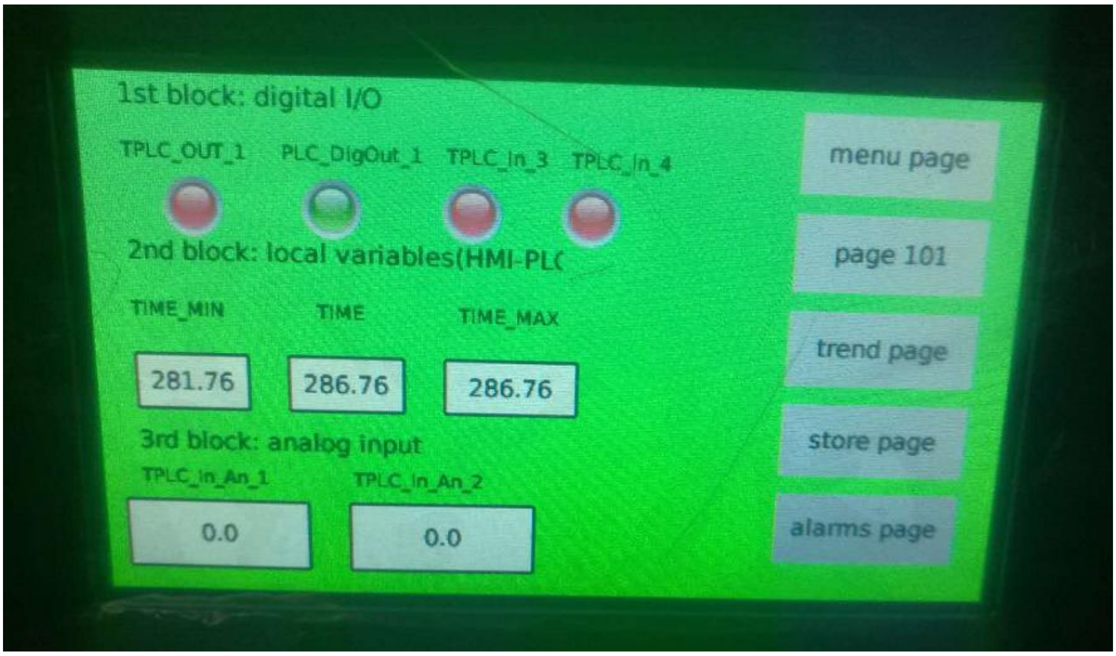

Figure 81. The interface of panel

And also from the HMI results, the second light which is connect to the PLC variable is turn on as green while the first light connect with TPLC value is off. It seems the TPLC value is internally changing and assign it's internal changing value to the PLC_DigOut_1, but it's outside value is keeping false no matter in PLC software and HMI interface. Think about it could be due to the variable type since TPLC_Out_1 is defined as a H type whose update is limited. A change of type has done from H to P where P type can update it's value every time. But the results doesn't make any difference.

So with this exercise, it is possible to get familiar with the most important parts design of pages and writing codes, further understanding of whole software can follow the tutorial inside the QT creator with the button 'help'. And one question is appear is that what's going on with the TPLC_Out_1, and how it can be used, since a PLC_DigOut_1 can be used in the same way and the better is it can be displayed on the panel interview, so why it's necessary to defined a TPLC value. This question may be solved as going deeply with the software. But anyway, the exercise is success and it shows the potential to use this hardware plus software to realize the control described in section 4 if proper sensors, and a model of tightening machine are available. And in the next exercise, some more complex control is going to be run and some available source of signal may be add to the STK board.

6.3 Exercise controlling of lights

In the exercise 2, the target is to control a light with in three ways. Two switches and a sound based control strategy. The whole control strategy is that, with the two switches, no matter each one of it change it's position, from up to down, or from down to up, the light will change it's condition from on to off or from off to on. This type of control of one light with two switches is very common with lights one the scales, it is possible to turn on the light before climb the scale, and when arrive the higher level, to turn off the light with another switch. And besides these two switches, the light is also controlled by the sound. It is based on the sound intensity, when the sound intensity is up to a certain value, the light will turn on and if the sound intensity goes down, the light will turn off automatically. It is reasonable to choose this type of control strategy cause when the sound intensity is big, it means people is passing through the light, so the light needs to be turned on. And it should be notices that when the light is turned on by the sound intensity, the switches will not change the state of lights, it will always turn on. And once the sound intensity is falling and reaching the threshold, the light will turn off not matter what the configuration of switches are. And thanks to the components on the STK board, at the first stage of the exercise, we use the LEDs of the STK board to simulate the in put digital signals from the switches, when the LED is on, it means the switch is in up position and vice versa. This LEDs can be turned on/off by the small switches below them. And another LED on the SKT board is used to simulate the light under control, and also the state of LED corresponding to the output digital signal, on means 1 and off means 0.

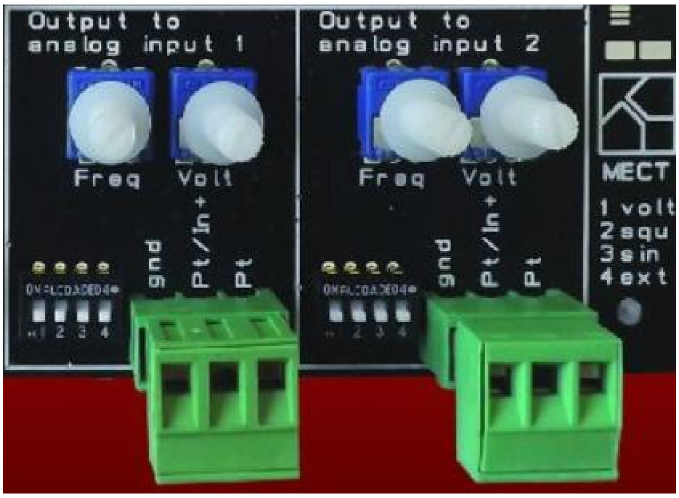

Figure 82. The analogue input region

Besides, the sound wave is acquired in two ways. The first way is to generate an analogue signal by the STK board itself. In the region we can see two trimmers and four switches. The two trimmers control the amplitude and frequency of the analogue input it generated, the ‘freq’ trimmer controls the frequency and ‘volt’ trimmer controls the amplitude. And by change the configuration of the four switches, it is possible to change the basic shape of the signal, such the sinusoidal shape or a triangle wave. With proper configuration and adjust on the STK board and also with proper coding in PLC software, a desired analogue signal can be generated which is simulating a sound wave used to control the light. And also, in the green part it is possible to connect some external analogue signal come from the real sound wave which is been used in the second stage of the exercise. Another way to acquired a control-used sound wave is by directly coding a function of PLC time, so a value is changing with time goes on and it can be chosen any value to simulate a real sound wave. The idea is to see whether the control works with the MCET starter kit.

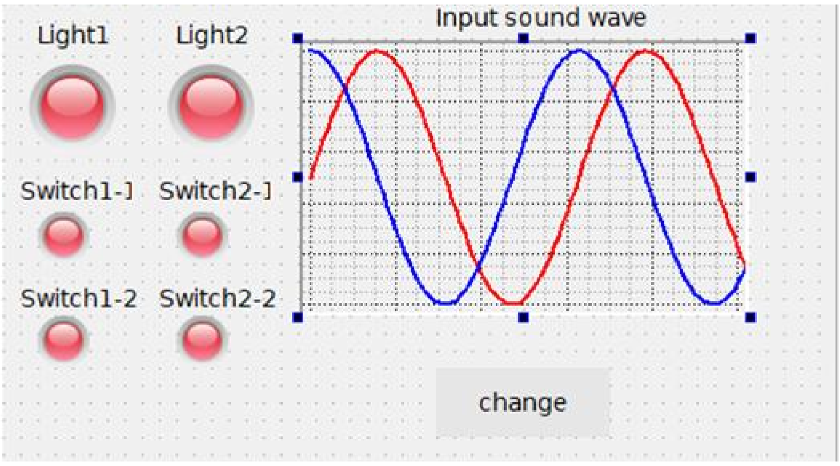

Figure 83. The working pages

After the pre prepare steps same as in last exercise, the design of page could be taken out. The page is designed as in figure 83. The two column are corresponding to the two source of analogue input, and the two big LEDs are the lights under control, the other four switches are used to control on/off. Also on the graph will present the curve of sound wave as a function of time. The bottom button ‘change’ is able to change page and on other page, some other charts and variables can be displayed.

```
t := real_to_int(PLC_time) mod 20;
PLC_AnOut_1 :=50* abs(10-t);
```

Figure 84. The set of analogue input

Then built the project and display the designed page on the TPAC 1007 panel, we can start to write the related coding. Before the way to set a function as the analogue input is introduces. The coding is shown in figure 84. Since the graph displayed on TPAC 1007 panel have an horizontal axis corresponding to the PLC_time which is a variable of type REAL according to the crosstalbe. First we need to change the variable type to store the value of PLC_time in to an integer variable ‘t’. And since the PLC_time is always increasing while the project is processing, we can set a period as 20 and make the analogue signal as a periodic function. So afterwards we can apply a function of t, and stored in the PLC_An_Out_1 which can be displayed on the TPAC 1007 panel. The function is set to be a triangle wave which has a period of 20 seconds can a maximum value 500 and minimum value 0.

```
 switch12 : bool;
  switch22 : bool;
  counter2 : int :=0;
  counter_sound2 : int :=0;

  t : int;
  tt : real;

END_VAR
  PLC_DigDir_8 := 1;
    PLC_DigDir_7 := 1;
 PLC_AnInConf_1 := 2;
 PLC_AnOutConf_1 := 2;
```

Figure 85. Coding for the configuration

At the most beginning, some intermediate variables are set with proper type. And then the variables related to the configuration on STK board are set to proper value. The first two variables named as PLC_DigDir are set to 1, means the LEDs they controlled are behavior as outputs, so they corresponding to the LEDs simulate the lights. Then the other two variables are related to the analogue signal, they are set to 2 according the tutorial which means the analogue signals are in a voltage form. And before write the control coding, it need to know the numerical information of the analogue input generated by STK board itself.

TPAC.Resource1.PLC_AnOut_1

Variable / Expression	Type	Value	Time	Quality	Format
TPAC.Resource1.PLC_AnOut_1	INT	150	2018-06-22-12:26:17.207	Good:	
TPAC.Resource1.PLC_AnIn_1	INT	4120	2018-06-22-12:26:17.207	Good:	

Figure 86. The value of analogue input

Since the analogue input can been seen from the TPAC 1007 panel, we can first download the coding up to now to the panel can start running the project, and see that the shape it is, and also in PLC software, the value of variable PLC_AnIn_1 can be traced so the frequency and amplitude can be gotten. First the third and fourth small switches in figure 82 are pushed up in order to generate a sinusoidal wave which is a little different form the describing on home page of MECT starter kit. Any way, with the small switches and the two trimmers we can firstly get the desired curve. And then combine the watch window shown in figure 86 the values can be seen has a maximum value over 4000, this value is very imprtant in the afterwards control part.

```
if( PLC_DigIn_3 = switch12) then
    switch12 := PLC_DigIn_3;
else
    counter2 := counter2+1;
    switch12 := PLC_DigIn_3;
end_if;
if( PLC_DigIn_4 = switch22) then
    switch22 := PLC_DigIn_4;
  else
    counter2:= counter2+1;
    switch22:= PLC_DigIn_4;
end_if;
PLC_DigOut_7 := int_to_bool(counter2 mod 2);
if( PLC_AnIn_1>2000 and PLC_DigOut_7 = false) then
    PLC_DigOut_7 := true;
   counter2 := 0;
end_if;
if(PLC_AnIn_1 <2000 and counter2 mod 2 =0) then
    PLC_DigOut_7 := false;
end_if;
```

Figure 87. The control coding

The control part are of two parts, one upper part is related to the control by switches and the lower par related to the sound control way. In the upper part, we can see, the current state of a switch will stored in the variable 'switch' , and when a new circle begins, the new state of switch will compare to the older one stored in variable 'switch', if they are the same, nothing happens but to store the state of switch again, on the contrary if they are not of same value, it means, a switch is pushed, so the 'counter' will add one to its value. The variable 'counter' is used to control the on/off of the light. As it can be seen that when the counter is odd, it controls the light on and if it is even, it controls the light off. It works obviously with one single switch. And under two switches, since the state of light will change every time the counter change it's value, which is perfect matches the target that every state change of switch state no matter which one will cause a state change of light, so this coding working perfectly to realize the target.

In the lower part, it is mainly realize the function which when the analogue value is higher than a threshold, 2000 for STK board generated analogue signal and 250 for the simulated analogue signal described by function, the light is turning on and vice versa. The hard point is to combine this part with the higher part since they control the light simultaneously. So, when the light is off and the sound intensity reaches the threshold, the light is on, and the 'counter' is set to be 0. The latter part is of high importance, imagine that without the setting of 'counter' value to 0 and with a condition describe below: in cycle 1, the switches doesn't change and the sound intensity is very high, the light is on and cycle 1 ends. In cycle 2 one switch changes and so the 'counter' is equal to one, since the light is already turned on by the sound intensity in last cycle, nothing will changed. And in cycle 3, no switches change but the sound intensity is lower, so the light is off but the counter is still one, it means in cycle 4 the light will turn on automatically which is not the case we want. So the counter is reset every time the sound intensity is high.

Then press F7 to build the project and check is there any errors and warnings, correct the errors of grammar and the coding can be downloaded to the TPAC 1007 panel and starting running..

Figure 88. The TPAC result

In the monitor the red curve is the sinusoidal wave we generated by STK board itself and it controls the Light 2, it can be seen now it's value is high and so the light is green which means on. The blue curve is the sound wave we generated by function and it controls the Light 1, and also it can be seen with a high value the light is turn on. But here some questions are generated on the graph displays the analogue signal. Since the blue one is generated by function and it is supposed to have an amplitude 500 and an triangle shape, but it can be seen that the shape is strange with many horizontal parts which the reason to cause it is not specified. And the red one is supposed to have an amplitude 5000, but in the graph it is lower than the blue one, it seems the although present in the same graph, they don't share the same scale. The scale of the graph can be adjusted in QT creator by set the properties of

ATCMgraph, but I actually don't find a completely way to set all the properties relate to the graph.

Figure 89. The STK board result

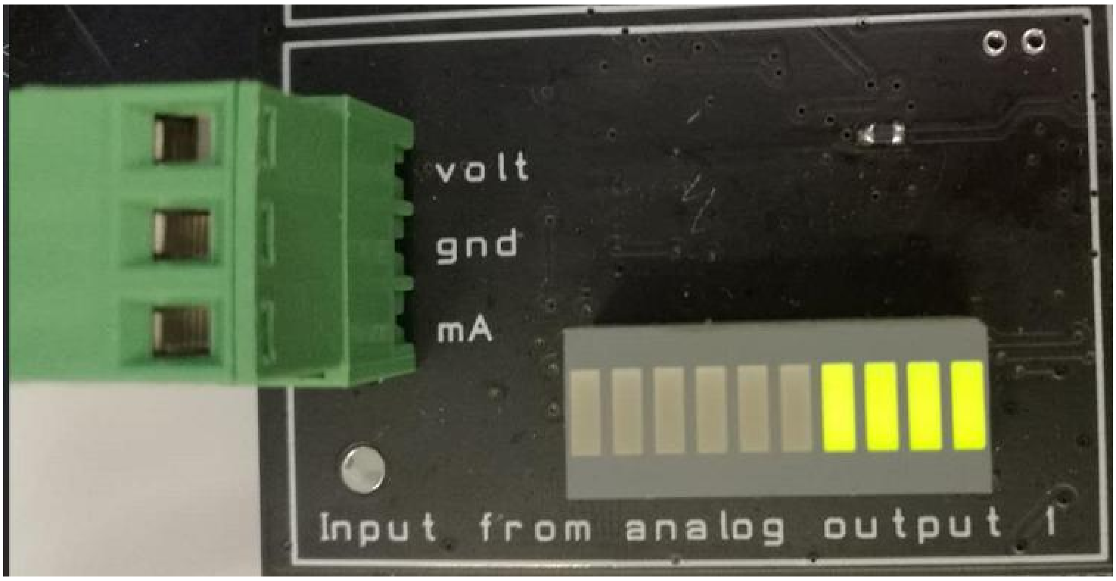

Figure 90. The STK board

In figure 89 and figure 90 shows the corresponding results of the STK board at the same time of figure 88. The two LEDs on are simulated the lights under control and they have the same state of lights in figure 88. And in figure 90 the yellow light bar are relate to the analogue output. Since during the coding we store the function generated analogue signal value in the variable PLC_AnOut_1, and the value of PLC_AnOut_1 has a relation of the number of yellow light bar, the light bar is another presentation of the variable analogue output amplitude.

Up to now the first stage is finished. And in second, it is supposed to use external signals to replace the self generated analogue signal and the function generated analogue signal. So a generator is connected to the STK board at green part in figure 82, and the amplitude and frequency of the analogue input can be tuned. But the results is not as I supposed. According to the panel graph present the analogue input and also the watch window of PLC software shows the value of analogue input, there is no analogue input received from the external. The process is first to tuned the trimmer to set the amplitude of self generated analogue signal to zero, but then the watch window and panel graph both show the analogue input is 0. Consider the variable PLC_AnInConf_1 may influence since it in charging the configuration, but all the value assigned to it from 0 to 2 doesn't influence the result.

So the second stage failed, and in third stage, I plan to use a external oscilloscope to monitor the analogue input signal generated by the STK board and the output analogue signal which set equal to the analogue input. If we can detect some analogue signal, it is meaningful that we can exchange data with other machines or controllers. But the result is also not good, on the oscilloscope it only can measure the amplitude change, but the frequency can't be calculated after even a long time, and also it can't show the sinusoidal wave as it supposed to be.

6.4 The conclusion of exercises

After the two exercises some conclusion of the MECT starter kit can be draw. It actually can realize the control but it has some problem on connection with others, no matter the connect from input and connect to outputs. Because of some specification such as power supply of the STK board and equipped micro controller, some small, common sensors in laboratory are not adequate to use with it. The MECT starter kit seems to work with some big, complicated industries sensors. And also, the connection with external is not work in a simple way since I failed in connecting it with some common generator and oscilloscope commonly used in DET located in Politecnico, so it works with some specific external device and also it may need some proper coding in PLC software to make a right configuration.

The MECT starter kit is definitely able to work with sensors and give outputs related to the inputs, but the way it how to be used especially the connection is still need to be specified.

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