

A MICRO SPRING PLUNGER GRIPPING MECHANISM DESIGN WITH PIEZOELECTRIC FORCE SENSOR FOR AUTOMATED HANDLING PROCESSES

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Abstract

In automated manufacturing processes, grasping devices and methods play a crucial role in the handling of many parts, components and work pieces. In this study, it is aimed to present a design an integrated gripping mechanism for the handling system of grinding process of an automotive workpiece. The system consists of a pneumatically activated guided rail cylinder, a spring loaded end position pushing mechanism, a spring force plunger and a piezoelectric force sensor for detecting workpiece presence. The gripper is designed and optimized through 3D Ansys Software for Static Loading. A prototype is built and applied on a grinding machine coupled with a hydraulic rotating cylinder. The proposed system exhibits highly scalable, flexible and robust handling features for robotic and automated applications, which can be easily adapted for a variety of gripping solutions.

Keywords: - Microgripper, piezoelectric force sensor, electro-mechanical grasping, grinding, automated loading

1. INTRODUCTION

In the last decade, several factors such as the increasing cost of human labor, the widespread of robotics automation and the decreasing cost of fixtures and mechanisms pushed the industry towards the development of new grippers and robotic hands. While in the past robot hands and industrial grippers were oriented to different goals, nowadays it is often difficult to distinguish a simplified robotic human-like hand from a complex industrial gripper (Fantoni, 2014). The fast growth in the field and the development of new grasping technologies merits a review of grasping devices and methods in production processes. In addition, the need for

more productivity is pushing automation towards new frontiers asking for more flexible, versatile, lightweight, and small grippers able to perform more functions than simple grasping and holding during handling.

Tadakuma (2011) summarized several grasping principles (Figure1), some of them mimicking the human fingers or animals' claws or jaws, or exploiting different physical effects. Some principles can be applied only at the microscale (e.g. acoustic levitation or laser tweezers), while others (Nah, 2007) proposed for micro-handling are now expanding beyond that field (e.g. Van der Waals forces).

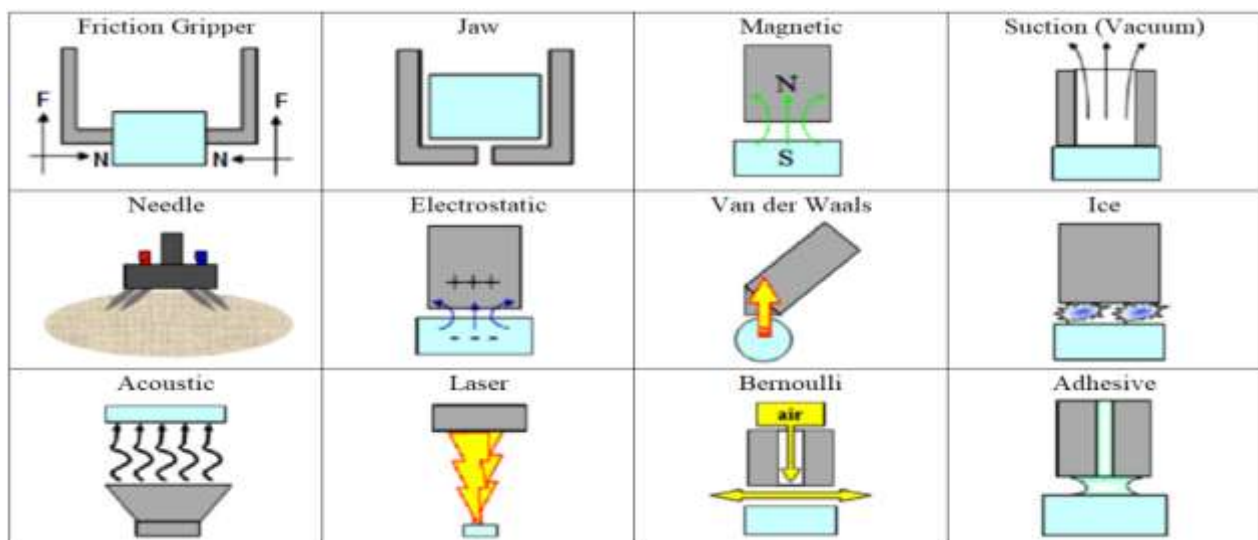


Fig 1: Grasping principles. Adapted from Tadakuma (2011)

Spring force plungers are widely used in tool grippers, which hold a plurality of tools in rack typemagazine that accommodates tools used in machine tools (Ogura, 2000). Generally, a tool exchanger is designed so as to allow the tools to be taken in and out in horizontally lateral directions, accordingly to prevent the tools from falling off, ball plungers are disposed in the vicinity of toolentrances of the arm portions of the tool grippers. The handling of small workpieces puts special demands on the gripping device, which are derived from the manufacturing process on the one hand and from the properties of the transferred parts on the other hand. Schlick (2001) proposes a tong gripper for microparts with a guiding mechanism based on flexure hinges and pneumaticactuation in order to meet the demand for high repetitive accuracy of the gripper in case of a rotational symmetrical part.

A piezoelectric element generates an electric field (and a measurable voltage from the field) in response to applied pressure (Gautschi, 2002). However, a piezoelectric element generates such electric fields only in response to changes in the applied pressure or force. In other words, a piezoelectric element conventionally acts as a dynamic pressure sensor. This by itself may be useful for measuring a physical contact, an axial or radial force in a gripper mechanism. The dynamic response may also be utilized in a Computer Numerical Control (CNC) where the mere presence of a short press is sufficient for a digital input recognition without the need for absolute pressure determination. (Leskinen, 2010). Such a typical industrial application consists of miniature ring load cell in a predefined measurement range, which is coupled with an amplifier module converting the signal into standardized outputs of ± 5 V, ± 10 V or 0(4)-20 mA. Amplified voltage or current can be directly used by the Programmable Logic Controller (PLC) as an analog input and can be programmed via delay-on, delay-off timer blocks. The latest generation of instrumentation amplifiers support Ethernet based fieldbuses such as Profinet, EtherCAT, EtherNet/IP or I/O interface, to meet the challenges of Industry 4.0. (URL 1)

In this study, a prototype of a miniature gripper mechanism for an automotive workpiece is built and tested on a grinding machine automatic loading system. The workpiece is picked up from the raw material pallet by a pneumatic gripper and transferred into the machine zone by a linear guide driven by a step motor. Then, the raw material is gripped by the proposed mechanism, which consists of a pneumatically activated high precision air slide table equipped with two inductive proximity sensors in both end positions, a spring loaded pusher mechanism, a spring force plunger, a guiding pin inside the hollow shaft, and a piezoelectric force sensor for detecting workpiece presence by measuring a change in compressive or tensile force. The workpiece is loaded into the pneumatic chuck by a hydraulic rotating cylinder and pushed towards the mechanical stop. The working environment of the mechanism is the interior of a grinding machine, which is highly abrasive, in splash of cooling oil and dimensionally restricted. The mechanism and its control system must be reliably designed to prevent crash, component failure or an explosion of the grinding wheel, which may result in an injury of the operator.

The authors want to emphasize the innovative design of a miniature grasping mechanism with a spring force plunger and the integration of the piezoelectric force sensor for a precise positional adjustment and workpiece detection. In this work, Autodesk Inventor® is used for the generation of preliminary 3D models, Ansys® Workbench is used for the structural analysis for dimensioning critical components. The proposed system exhibits highly scalable, flexible and robust handling features for robotic and automated applications, which can be easily adapted for a variety of gripping solutions. In the preceding sections, mechanical design, control mechanisms and finite element strength analysis will be discussed in further detail.

2. MECHANICAL DESIGN

The mechanical design is a pneumatic tool assembly, in which an adjustable spring force plunger and a guiding pin is used as the locking mechanism. The description of the locking mechanism is illustrated in Figure 2.

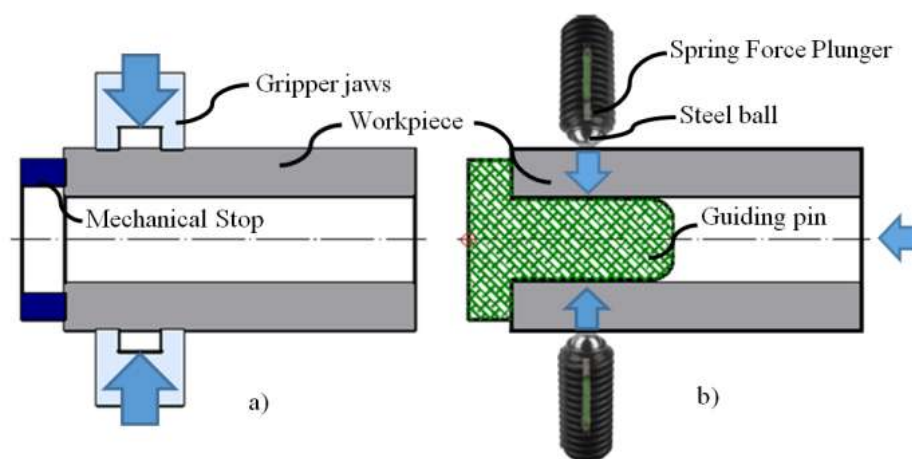


Fig 2: Schematic representation of a cylindrical workpiece a) gripping with jaws b) gripping with spring force plunger

The cylindrical hollow hole and the geometry on the outside diameter of the workpiece allows frictional locking during loading and unloading. The workpiece is positioned inside and outside of the chuck by a pneumatic precision air slide table, the positioning is controlled by two proximity

switches at both end points. Then, the workpiece is precisely pushed towards the end stop by the pusher spring. The change in force, i.e. the loading activity is measured and controlled by a piezo force sensor, in both compressive and tensile directions in Figure 3.

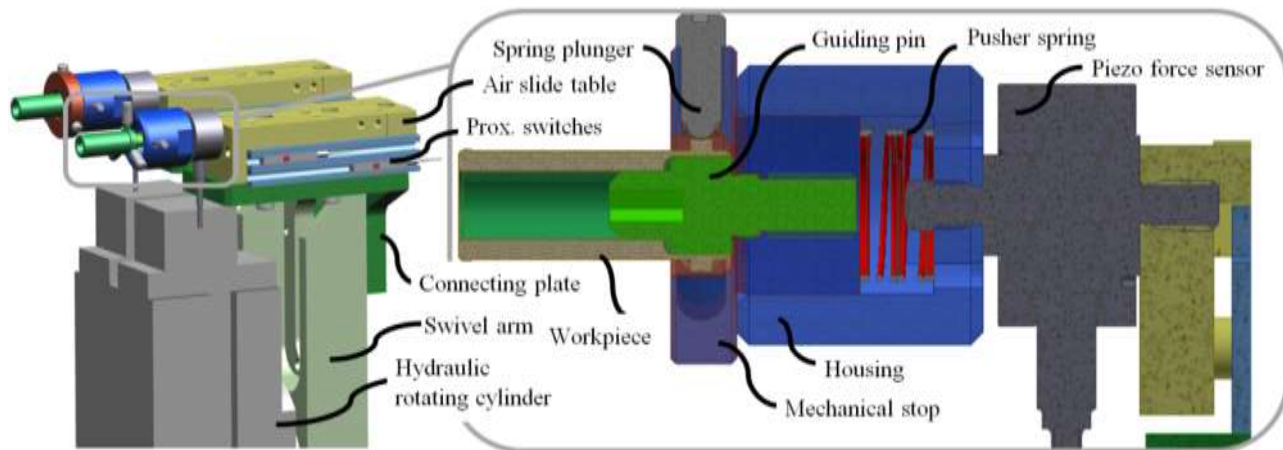


Fig 3: Mechanical Design of the loading mechanism

The mechanical design optimization is mainly concentrated on four aspects: The selection of the air slide table, the selection of the pusher spring, the selection of the spring plunger and the selection of the piezo force sensor.

2.1 Selection of the Air Slide Table

When loads are applied to the air slide table section marked with the arrow at the full stroke, the table displacement of the air slide table are given in Figure 4. One can calculate the total load from the preliminary design as $W=3.1\text{ kg}=30\text{ N}$. For a practical value of the positioning displacement can be selected as $\Delta x \leq 0.02\text{ mm}$. Due to the mechanical constraints, a minimum extraction length of $L_{min}=25\text{ mm}$ is required. It can be read that the MXQ8-30 selection satisfies the criteria.

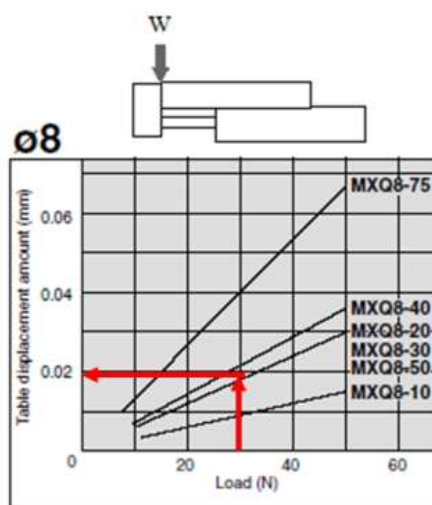


Fig 4: Selection of the air slide table with permission of SMC Inc. Adapted from (URL2)

2.2 Selection of the Pusher Spring

The pusher spring has to be designed to overcome the pneumatic force, applied by the pneumatic cylinder as in retracted position to the mechanical stop. The force is calculated from $F_p=PA$, where $P=0.15\text{ MPa}$ taken as the minimum operating pressure, and A is taken as the sum of the cross-sectional areas in double piston arrangement with the diameter of $d=8\text{ mm}$. Area can be calculated as $A=50.26\text{ mm}^2$ and the piston force can be found as $F_p=15.1\text{ N}$.

In order to perform the “pushing” effect, the force applied by the pusher spring at maximum compression must be less than this force applied by the piston towards the mechanical stop. That is $F_s < F_p$, where the spring force can be calculated from $F_s=k\Delta x$, where $\Delta x = \Delta x_{pre} + \Delta x_{load}$, namely the sum of compressive pre-deflection and the movement inside the housing. From the mechanical constraints we can preselect a spring from the catalog Gutekunst VD-117N. The dimensions and catalog values of the given are given as: $d_i=9.8\text{ mm}$, $d_o=12.9\text{ mm}$, $n=5$, with maximum dynamic load $F_{dyn}=12.35\text{ N}$. We can check the selection with $F_s < F_p$, i.e. $12.35\text{ N} < 15.1\text{ N}$ is satisfied. Therefore the selection is accurate and we can proceed with the next step.

2.3 Selection of the Spring Plunger

The function of the spring plunger is simply to “lock” the workpiece. The locking force has to be designed so as not to allow movement at dynamic acceleration during loading and unloading. Note that the spring plungers are in rotated orientation of $3\text{ pieces} \times 120^\circ$ each to allow the misalignments are centered and smooth locking and unlocking is guaranteed. From Figure 5, we can select type 03031-04 Spring plunger with hexagon socket and ball. The catalog values are given as the initial spring force and

maximum spring force as $F_{min}=4\text{ N}$, $F_{max}=10\text{ N}$. We can calculate an average spring force as $F_{al}=6\text{ N}$ in $3 \times 120^\circ$ arrangement the total normal and the axial and radial force

can be calculated as $F_a=3 \times F_{al} = 18\text{ N}$. Note that the calculated force satisfies the criteria $F_s < F_p < F_a$, where locking and the intended function is satisfied.

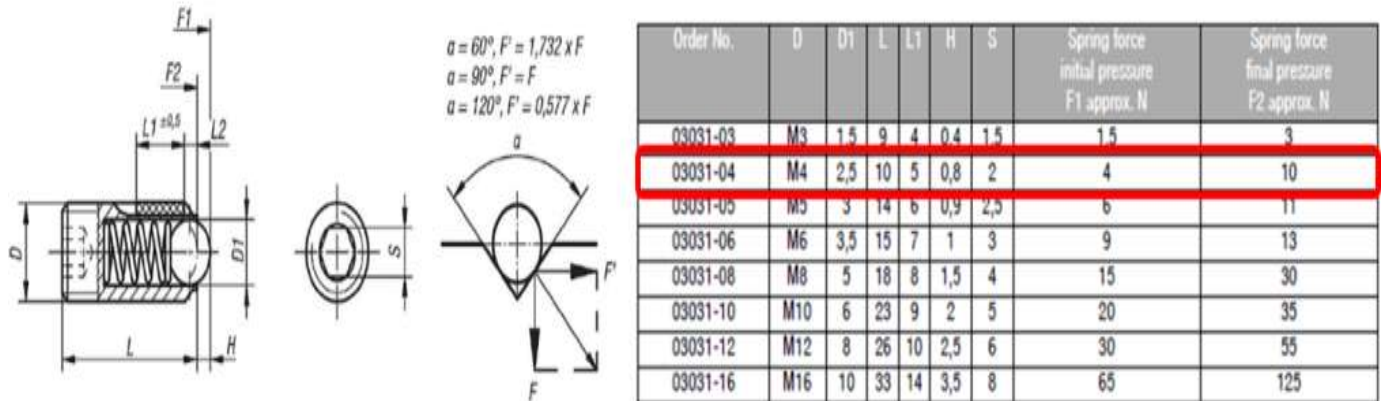


Fig 5: Selection of spring plunger. With permission of Norelem. Adapted from (URL 3)

2.4 Selection of Piezo Force Sensor

For the selection of the miniature load cell i.e. the piezo force sensor, the most important engineering input is the measured force and the bidirectionality. The sensor is to be selected to measure the whole range of the pneumatic force, applied by the pneumatic cylinder to the mechanical stop. The force is calculated from $F=PA$, where $P=0.5\text{ MPa}$ taken

as the operating pressure, and A is taken as the sum of the cross-sectional areas of the two pistons calculated as $A=50.26\text{ mm}^2$. The operating force can be calculated as: $F_p=50.2\text{ N}$. From the catalog, the available measuring ranges can be read as : $0 \dots 20\text{ N}$, $0 \dots 50\text{ N}$, $0 \dots 100\text{ N}$, $0 \dots 200\text{ N}$. Therefore type 8432-5050 with the measuring range $0 \dots 50\text{ N}$ is selected (Figure 6).

Model 8432 with bidirectional overload protection

Order Code	Measurement Range	Dimensions [mm]		
		ø D	H	Thread T
8432-5002	0 ... 2.5 N	25.4	21.9	M 4 x 0.7
8432-5005	0 ... 5 N	25.4	21.9	M 4 x 0.7
8432-5010	0 ... 10 N	25.4	21.9	M 4 x 0.7
8432-5020	0 ... 20 N	25.4	21.9	M 4 x 0.7
8432-5050	0 ... 50 N	25.4	21.9	M 4 x 0.7
8432-5100	0 ... 100 N	25.4	21.9	M 5 x 0.8
8432-5200	0 ... 200 N	25.4	21.9	M 5 x 0.8
8432-5500	0 ... 500 N	25.4	21.9	M 5 x 0.8
8432-6001	0 ... 1 kN	31.8	23.9	M 6 x 1.0
8432-6002	0 ... 2 kN	38.1	26.7	M 6 x 1.0



Fig 6: Selection of piezo force sensor. With permission of Burster. Adapted from (URL 4)

3. FINITE ELEMENT ANALYSIS

In order to define the critical components, the designed model is analyzed through finite element analysis software Ansys. The geometry data has been subjected to external forces at the workpiece face, resulting from the pneumatic pushing inside the chuck fixed stop. The axial component can be calculated as $F_a=70\text{ N}$ (see Sec.2.4) at the maximum

operating pressure $P_{max}=0.7\text{ MPa}=7\text{ bar}$ of the pneumatic piston, the radial component has been calculated as $F_r=35\text{ N}$, that is the total moving mass and forces due to the possible misalignment deformation of the moving mechanism when the workpiece is pushed inside the chuck towards the fixed stop. Figure 7 shows the geometry with the external forces and Equivalent (von-Mises) Stress.

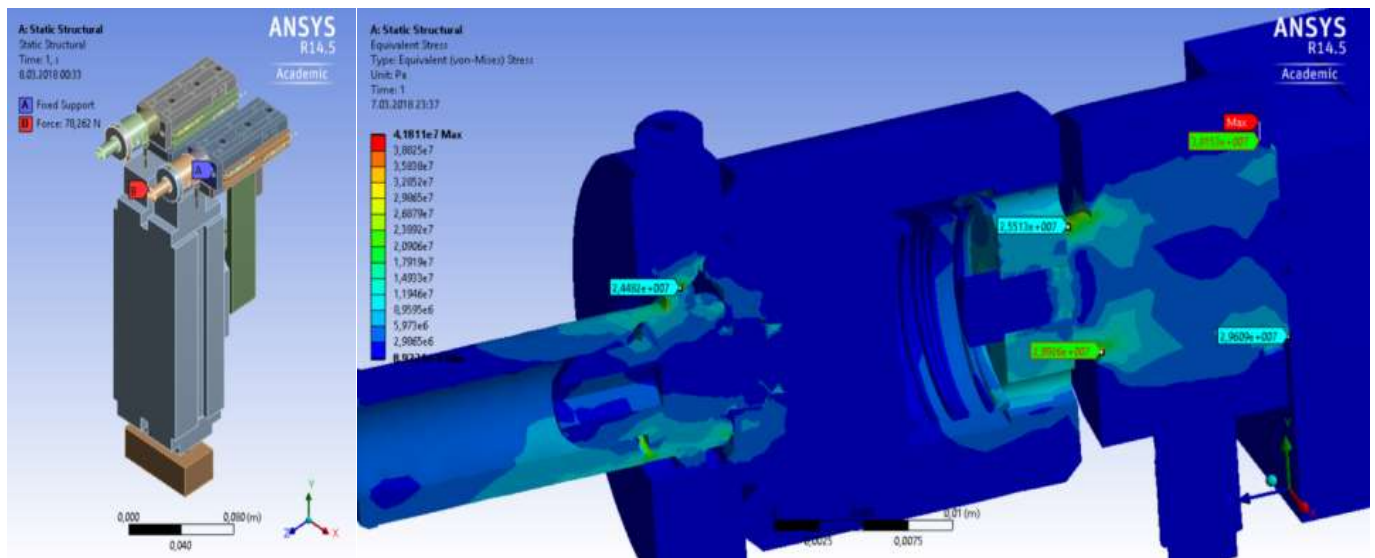


Fig 7: On the left: Geometry and forces on Static Structural. On the right: Equivalent (von-Mises) Stress

The maximum stress has been found in the connecting screw of the housing to the piezo force sensor. This section has been carefully analyzed within the geometrical constraints and preferred material properties. To improve the geometry, the screw size M3 from the preliminary design has been enlarged to M4. Also the material of the housing has been changed from 1.4305 Stainless steel to case hardened

steel1.7131 inductive hardened to 0.5 mm depth with a tensile strength of 780-1100 N/mm² and a surface hardness of HRC 58 +2. By the use of finite element analysis, the geometry and the material properties have been improved at the critical sections. Using the fatigue tool, in Figure 8, the minimum factor of safety at this section has been simulated as SF=2.06.

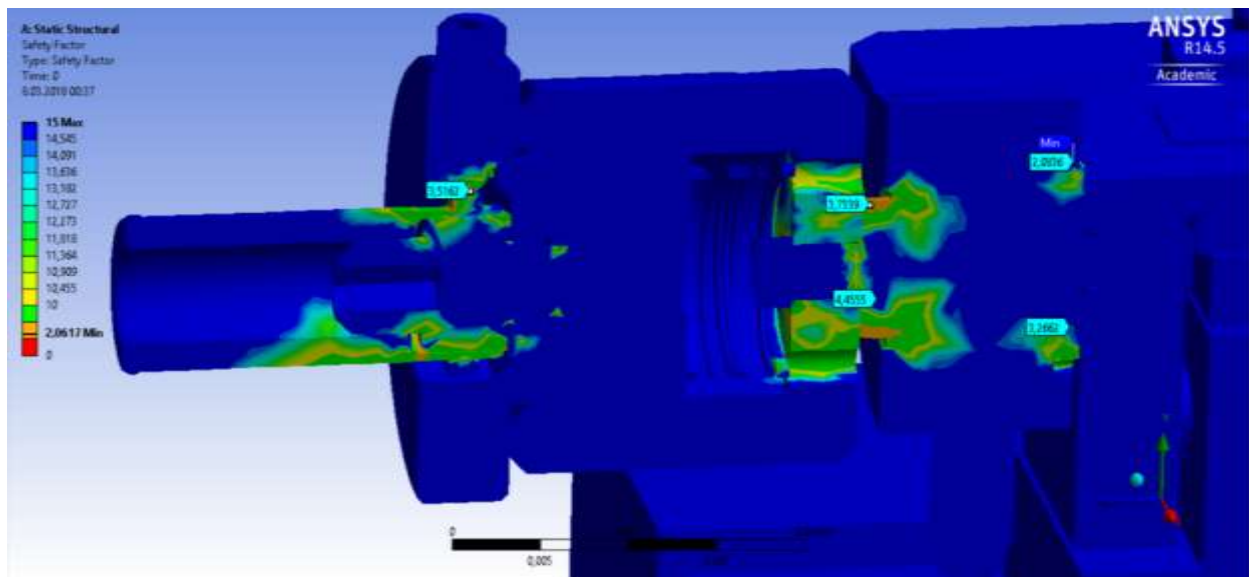


Fig 8: Safety factor at most critical cross section

4. DESIGNING THE CONTROL ALGORITHM

The schematics of the loading function and the force measurement is illustrated in Figure 9. The pneumatic piston is extended so as to allow the workpiece contact with the fixed stop. During this motion, the pin is pushed inside the housing and compresses the spring. This relative change in compressive force is then measured by the piezo sensor.

Then the workpiece is gripped by the chuck and the pneumatic piston is retracted towards the opposite position. Similarly, a change in force in tensile direction is then measured by the piezo sensor. This feature allows the precise recognition of the loading and unloading function, and not only the workpiece existence, but also the correct adjustment of the workpiece position relative to the fixed stop.

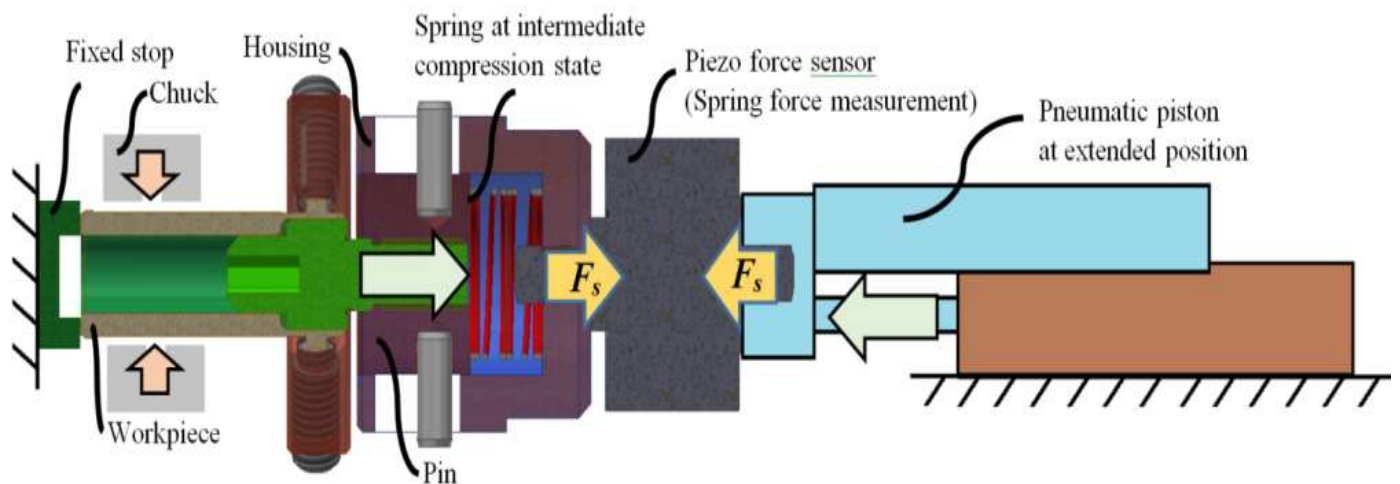


Fig 9: Loading function and the free body diagram of the piezo force sensor.

The measurement of the voltage starts by the extraction output signal of the pneumatic piston. The measured voltage value input V_m to the PLC (Programmable Logic Controller) is controlled within the preset range of $V_{min}=5$ V and $V_{max}=8.5$ V. The measured timing t_m is controlled by timer preset values $t_{min}=0.25$ s and $t_{max}=3.5$ s.

The loading algorithm is judged in three possible scenarios as illustrated in Figure 10.

Scenario 1: Start Measurement \rightarrow When $V_m > V_{min}$ Start $t_m \rightarrow$ When $V_m < V_{min}$ Stop $t_m \rightarrow$ If $t_{min} < t_m < t_{max} \rightarrow$ OK

Scenario 2: Start Measurement \rightarrow If $V_m < V_{min}$ within $t_{max} \rightarrow$ Incomplete

Scenario 3: Start Measurement \rightarrow If $V_m > V_{max}$ within $t_{max} \rightarrow$ Crash

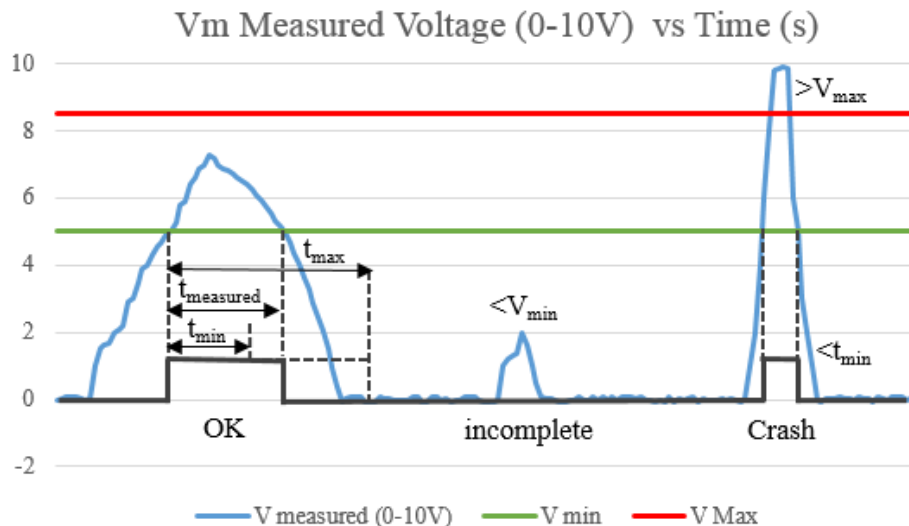


Fig 10: Programming scenarios of piezo force sensor measurement

5. BUILDING THE PROTOTYPE

Based on the proposed design, fabrication and tests of a pneumatically actuated spring force plunger gripping mechanism were performed. The geometry design and the material stresses were considered through the finite element analysis. The simulation model was used to study in detail profiles of von Mises stresses and deformation. The maximum stress in the connecting screw has been calculated and the factor of safety for the critical stress values for fatigue is found. In the most critical section, the

dimensioning and the material properties have been improved. The use of piezoelectric sensor allowed a safe and reliable control algorithm of the workpiece presence, as well as the recognition of possible adjustment errors and component failures. The software of the grinding machine (Figure 11) has been reprogrammed to detect and to react in three scenarios for OK, incomplete and crash cases. Series production results of more than 1000 working hours have proven the good performance of the gripper (Figure 12) .



Fig 11: On the left: Handling system and grinding machine. On the right: Gripper mechanism



Fig 12: On the left: Gripper and workpiece. On the right: Unload from chuck when the pneumatic piston is extended

6. CONCLUSION

In this study, it is aimed to present a design approach “from design to manufacture” of an integrated gripping mechanism for the handling system of grinding process of an automotive workpiece. The system consists of a pneumatically activated guided rail cylinder, a spring loaded end position pushing mechanism, a spring force plunger and a piezoelectric force sensor for detecting workpiece presence and . A prototype is built and applied on a grinding machine coupled with a hydraulic rotating cylinder. By the use of finite element analysis, the geometry and the material properties have been improved at the critical sections. An algorithm for the measured force of the piezoelectric force sensor is developed and the Programmable Logic Controller (PLC) of the grinding machine has been reprogrammed for intended control function. The prototype has been tested under serial manufacturing conditions and proved successful performance for more than 1000 hours of operation.

Limited space, harsh environment and safety requirements of the grinding machine interior placed additional constraints on the design, where simple, reliable mechanical solutions with sophisticated control electronics were

required. The design must ensure a service-free, adjustable loading mechanism and avoid more complex solutions like vacuum, pneumatic gripping, motors and robotics, and keep the dimensional size at a minimum. Thus, a scalable and robust gripping and automated control mechanism has been presented, that can be adapted for a variety of gripping solutions.

Future work can be directed into building an integrated micro gripper that can be scaled down to very small dimensions. Two distinct functions, namely the gripping with spring plunger and piezoelectric sensing and activation might be combined into an industrial product to allow handling of micro parts and to provide control and feedback.

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