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A novel ball joint wear sensor for low-cost structural health monitoring of off-highway vehicles

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1 sensor for the ball joint is firstly aimed at monitoring the damage of the ball joint placed
2 between the steering actuator and the wheel spindle, since failure of the joint leads to
3 complete loss of steering action. However, the sensor can be applied to any application
4 involving a safety-critical ball joint (e.g. the front suspension of a vehicle). The present work
5 describes the conceptual design and development of the whole mechatronic sensor, which
6 includes the mechanical joint sensor and the electronic board which manages the system.
7 Validation of the ball joint wear sensor, which was performed on an agricultural tractor
8 through tests on a track, proved the reliability of the proposed solution.

9

10

11

12 **Keywords:** ball joint, wear sensor, preventive diagnostic, active safety, vehicles, wireless node,
13 ultra-low power consumption.

14

1 **1. INTRODUCTION**

2 Ball joints are spherical bearings obtained by coupling a ball-ended pin with a spherical
3 socket to allow free rotations about a single point. They are frequently used in off-highway
4 vehicles, where ball joints connect the steering actuator to the wheel spindle. In the
5 automotive field ball joints are used, in addition, to connect the members of the front
6 suspension. Consequently, ball joints are a very critical component, since their failure causes
7 either a complete loss of the steering action or determines a sudden loss of vehicle handling,
8 thus leading to severe accidents. Despite this, no simple and low cost solutions are currently
9 available in order to actively monitor the structural integrity and the residual service life of ball
10 joints. Only passive solutions, where the joint is manually checked by an operator, are
11 available, see for example [1].

12 Wear originated by the relative movement between the ball and the socket is the most
13 critical issue for this component, which can lead to failure also in long life ball joints [1]-[3], as
14 demonstrated by a number of publications in the literature [4]-[9]. In order to reduce the
15 friction and prevent wear, actual ball joints contain lubricating grease between the ball and the
16 socket interface. Possible failure of the polyurethane sleeve that seals the ball joint and
17 contains the grease leads to double drawback: the leak of the lubricant and the chance of
18 having dirt and debris contamination of the joint. As a consequence, ball joint degradation
19 occurs due to wear of the ball socket system, up to the complete failure which could cause
20 catastrophic consequences (Figure 1).

21

22 Smart ball joint solutions including wear sensors were patented in the last years [10]-[14].
23 However, such solutions suffer from some drawbacks: some of them [10]-[12] need visual
24 inspection, thus preventing the development of automatic methods; other solutions [13]-[14]
25 monitor wear through an electric circuit whose operation relies on the electric contact

1 between the ball and the socket. The wear of the system components (e.g. ball) originates a
2 gap between the ball and the socket that opens the circuit, largely increasing the electrical
3 resistance. The main limitation of such solution is its considerable energy consumption, which
4 would require a wired connection to power the sensor, practically impossible given the
5 position of the joint.

6

7 In this scenario, this paper presents an innovative ball joint wear sensor enabling remote
8 diagnostic, which overcomes the limitations of the existing solutions. The peculiar features of
9 the proposed ball joint wear sensor that make clear how this work contributes to the advance
10 of the technology in the sector are:

- 11 I. there are no other active sensors on the market for this and safety-critical ball joint;
- 12 II. the sensor has a ultra-low power consumption and thus can be self-powered
13 through energy harvesting;
- 14 III. it features wireless connectivity;
- 15 IV. it is low cost;
- 16 V. it has a small size and simple architecture;
- 17 VI. its simple architecture makes possible an easy integration into existing ball joints.

18 The wear sensor is able to continuously monitor the wear level of the joint and to measure
19 the joint acceleration. Through wireless connectivity, the sensor periodically sends this
20 information to an electronic central unit (ECU), which collects data from all the wireless sensor
21 nodes on the vehicle. It is worth noting that the information provided by the developed sensor
22 node enhances the overall safety of the vehicle since they monitor the residual service life of
23 the ball joint and thus allow preventive maintenance and diagnostics.

24 The design and development of the ball joint wear sensor was performed according to the
25 quality function deployment method [15]. The work involves two steps. The first step involves

1 the conceptual and detailed design phase of both the mechanical system and electronic circuit.

2 The second step develops the prototype and validates it experimentally.

3 The results show that the proposed ball joint wear sensor represents a valuable solution for
4 structural health monitoring of off-highway vehicles. The same system can be applied to
5 different fields, e.g. automotive or other systems where a ball joint is used, thus contributing
6 to improve the safety.

7 The work was supported by the ISOTRACTOR project [16], which was motivated by the need
8 to improve safety in tractors and off-highway vehicles, since national and international
9 statistics confirm that tractor accident is one of the highest causes of fatality. For example,
10 about 150 fatalities per year occurred in the last years in Italy, while about 100 fatalities per
11 year occurred in the United States [17]-[22], mainly caused by human errors. In this scenario,
12 there is an evident need for on-board control systems capable to actively prevent dangerous
13 operations, such as taking steep paths, thus enhancing machinery operator safety. The ball
14 joint wear sensor was developed in cooperation with Ognibene S.p.A., and tested on an actual
15 steering system mounted on commercial tractors.

16

17

1 **2. SYSTEM DESIGN**

2 Figure 2 shows the sketch of the ball joint that is installed in steering systems of off-highway
3 vehicles having a power range from 50 Hp to 100 Hp. This ball joint connects the hydraulic
4 cylinder piston rod (1) to the wheel spindle. The ball-ended pin (6) is pushed by the lower
5 bearing (3) and the spring (4) against the upper bearing (2). The friction between the ball-
6 ended pin (6) and the upper bearing (2) is reduced by Molykote grease, which is confined by
7 the polyurethane sleeve (8). The use in rough terrain can damage the polyurethane sleeve of
8 the ball joint: the lubricant is washed away and the joint starts to wear. The aim of this work
9 was to design and develop a wear sensor for the ball joint, in order to allow real-time
10 diagnostic and preventive maintenance of the system.

11 Three main constraints have driven the wear sensor development. First, ultra-low power
12 consumption. Second, a simple integration with the actual ball joint structure. Third, an easy
13 applicability to different ball joints. Table 1 collects all the customer needs and their
14 correlation with quantitative technical specifications.

15 According to the procedure proposed by Ulrich and Eppinger [15], the customer needs and
16 technical specifications were organized in the house of quality, not reported here for the sake
17 of brevity. The house of quality, together with a functional diagram of the system, have
18 oriented the whole concept generation phase.

19 This Section describes both the design of the ball joint wear sensor and the development of
20 the electronic circuit of the system management.

21
22 **2.1. Design of the ball joint wear sensor**

23 Figure 3 shows the concepts proposed for the ball joint wear sensor inspired by the
24 preliminary investigation of the technical literature ([10]-[14] and [23]-[37]). Concepts shown
25 in Figure 3a-d rely on monitoring the resistance of an electric connection, which is either very

1 low (i.e. short-circuit, Figure 3a, 2c, and 2d) or very high (i.e. open Figure 3b) during normal
2 operation, and it switches to very high and very low value when wear occurs. The circuit is
3 built between the ball pin and the outer case (Figure 3a), or between the lower bearing and
4 the ball pin (Figure 3b). By contrast, in Figure 3c and 2d an insert containing different electrical
5 paths is placed in the thickness of the lower bearing or through a hole in the outer case and
6 upper bearing respectively. All these solutions rely on the idea that the wear of the ball joint
7 changes the electrical conductivity of the medium placed in between two conductive elements
8 of the circuit.

9 The solution illustrated in Figure 3e correlates the wear to the lack of lubricant inside the
10 room of the ball joint, which is detected by measuring the magnetic permeability of the
11 lubricant itself. Another solution is proposed in Figure 3f where the relative displacement
12 occurring during wear between the joint cap and the ball pin is measured using a displacement
13 transducer.

14 These concepts were qualitatively examined and quantitatively evaluated against the
15 technical specifications reported in Table 1, weighted on their importance. Through a classical
16 screening and scoring matrix [15] (not shown for concision), the concept in Figure 3b was
17 chosen. Since the relative importance of the technical specifications is directly related to the
18 priority of the client needs, which has been defined at the beginning of the project, no
19 sensitivity analysis to these weights was performed.

20 Figure 4 shows the detailed technical sketch of the concept proposed according to Figure 3b.
21 This solution shows three main advantages compared to those proposed in Figure 3 and
22 compared to the patents traceable in the literature [10]-[14]. First, the wear sensor relies on
23 an open circuit in normal conditions, hence the power consumption is zero unless the failure
24 occurs. Second, this solution is simple, easy to be integrated into the current architecture of

1 ball joints and thus inexpensive. Third, this solution is more reliable compared to other
2 concepts in Figure 3.

3 The operating principle of the wear sensor is based on the variation of electrical resistance
4 between the pin-ball (part 6 in Figure 4) and the upper bearing (part (2) in Figure 4). In normal
5 conditions (no damage occurred), the upper bearing (part 2 in Figure 4) is coated by an
6 insulating shield to achieve a very high resistance, i.e. an open circuit between the bearing and
7 the ball (part 6 in Figure 4). This conical bearing is pressed against the ball-ended pin by a
8 conical helical spring. In case of a lack of lubricant or in case the system is not correctly sealed
9 thus contaminants get inside the joint, under working loads the wear occurring on the surface
10 of the bearing damages the insulating layer. Through the cable connected to the bearing by
11 means of a rivet (part 9 in Figure 4) applied in the center hole, it is possible to measure the
12 electric resistance between the bearing and the ball (up to short circuit condition): the lower
13 the electric resistance, the higher the wear in the system. In conclusion, this wear sensor
14 monitors the degradation of the upper bearing (part 2) in the ball joint, which is the most
15 critical element and leads to complete failure of the joint (see Figure 1).

16

17 **2.2. Design of the electronic circuit**

18 The proposed wireless sensor node allows enhancing the overall safety of the system where
19 the joint is used: the wear status of the joint and the accelerations to which is subjected are
20 delivered to a dedicated ECU which can use these data for preventive maintenance and
21 diagnostics purposes. The system is comprised of two main components: the on-joint sensor
22 (JS) and the on-vehicle control unit, i.e. the Data Manager (DM).

23 Figure 5 shows the electronic system architecture. In this paper we considered the case
24 study of a joint used in off-highway vehicles: the DM device, designed to be positioned on the

1 cabin of the tractor works as the access point for the data transmitted from the JS and other
2 wireless sensors on the vehicle.

3 Thanks to the Control Area Network (CAN) bus connectivity of the DM, the received data can
4 be transmitted to the electronic systems onboard and used in combination with other data to
5 monitor the working conditions of the whole vehicle.

6 The JS is in charge to sense periodically the wear level of the joint and to measure the
7 accelerations occurring during its operation. After each sensing operation, the JS sends the
8 data together with a unique device identifier (i.e. ID) to the DM. In this way the DM can collect
9 data from more than one wireless sensor installed on the vehicle without data conflicts.

10

11

1 3. PROTOTYPE DEVELOPMENT

2 3.1. Ball joint including wear sensor

3 Figure 6 shows the prototype of the ball joint including the wear sensor manufactured
4 according to the technical drawing in Figure 4. The upper cup (part (5) in Figure 2) and its
5 locking system were slightly modified in order to allow rapid disassembly of the joint, thus
6 simplifying periodic inspections during tests. All other parts of the system belong to a standard
7 ball joint provided by Ognibene S.p.A.. With reference to the sketch shown in Figure 2, the
8 ball-ended pin (6) is made in quench-tempered steel. Two different materials were considered
9 for the upper bearing (2): carburized and hardened mild steel or aluminum. The lower bearing
10 (3) was made with the same carburized and hardened material as the upper bearing. The wires
11 come out from the center of the joint cup through a plastic coupling. The sleeve (8) is made of
12 polyurethane having grade 385E, with hardness equal to 85 ShA. All the system is locked by a
13 plastic-stop nut (7). The electrical connection to the upper bearing was obtained by welding a
14 wire to a rivet which is then fixed to the upper bearing (2).

15 Three different insulating layers were investigated for the upper bearing: i) a coating made in
16 Rilsan, which is a blend of polyamide 11 and 12 (Table 2); ii) a coating made in Loctite Nordbak
17 7227 [38], which is a two component, ceramic reinforced epoxy, providing a high gloss, low
18 friction insulating coating (Table 3); iii) an aluminum upper bearing which is coated by a thin
19 electrically non-conductive alumina layer originated through anodic oxidation of the bearing
20 itself.

21

22 3.2. Electronic system

23 **Joint Sensor.** Figure 7 shows the simplified block diagram of the implemented Joint Sensor
24 (JS) incorporating the wear sensing circuit (bottom left block) described in the former sections.
25 The core of the device is an ultra-low power microcontroller (μ C) of the MSP430 family from

1 Texas Instruments, which achieves good performances with ultra-low power consumption (i.e.
2 $\approx 250\mu\text{A}$ when running at 1MHz, and $\approx 500\text{nA}$ in sleep mode) and embeds several
3 communication interfaces (i.e. UART, SPI, I²C). The JS is provided with an inertial sensor
4 (LIS3DH, 3-axial MEMS accelerometer from STMicroelectronics) for detecting the motion and
5 measuring joint accelerations. The adopted accelerometer consumes only $10\mu\text{A}$ with 100Hz
6 sampling frequency, while draining only 500nA in power-down mode. When in active mode,
7 the sensor can measure acceleration with maximum frequency of 5 kHz and full scale up to
8 $\pm 16g$. The μC periodically polls the accelerometer to detect the presence of vibrations, which
9 allows detecting if the joint is on duty.

10 In order to further reduce the JS power consumption, a Dynamic Frequency Scaling (DFS)
11 algorithm has been implemented to modulate the clock frequency according to the working
12 condition of the vehicle. In particular, when the vehicle is on duty, the clock frequency rises up
13 to 1MHz or 8MHz depending on the particular task (e.g. joint wear sensing or accelerations
14 measurements). By contrast, when the joint is off duty, the clock frequency is reduced to 200
15 kHz.

16 The wireless communication between JS and DM devices is implemented using the low cost
17 CC2500 low-power transceiver from Texas Instruments which can be easily controlled through
18 a SPI communication by adding only few external components. This transceiver is intended for
19 the usage in the 2.4GHz ISM (Industrial, Scientific and Medical) and SRD (Short Range Device)
20 frequency band, being IEEE 802.15.4 compliant. Its data rate can be configured via software up
21 to 500 kBaud, while typical current consumptions are 400nA when the transceiver is in power
22 down mode, 21mA when it is in transmit mode with an output power of +1dBm, and 13.3mA
23 when it is in receive mode.

24 The wear level of the joint is measured by means of a very simple circuitry. The basic
25 principle is based on the classic voltage divider where the output voltage is the voltage drop

1 across the joint, V_{JS} , that varies over time during the normal joint operation from several mega
2 ohms (new joint) to few ohms (worn out joint). This voltage is a fraction of the input voltage of
3 the divider (i.e. the supply voltage of the sensor node, V_{Supply_JS}) and is proportional to the
4 impedance measured on to the ball of the joint (i.e. between the upper bearing, part (2) in
5 Figure 2, and the upper cup, part (5) in Figure 2), accordingly with equation (1):

$$V_{JS} = V_{Supply_JS} \frac{(R_2 // R_{JS})}{R_1 + (R_2 // R_{JS})} \quad (1)$$

7
8 where R_1 and R_2 are the voltage divider resistors and R_{JS} is the resistance of the joint sensor
9 indicating the wear level. The ON-resistance of the solid state switch is around 1 ohm, while R_1
10 and R_2 have to be chosen in the order of ten-hundreds of kilo-ohm in order to minimize the
11 node power consumption. Consequently the voltage drop across the solid state switch has
12 been neglected in equation (1).

13 The μC periodically drives an ultra-low power solid state switch from Texas Instruments, i.e.
14 TS5A3159, which enables the sensing circuitry. When the switch is closed, the sensed
15 impedance value, R_{JS} , is acquired through the Analog-to-Digital Converter (ADC) embedded in
16 the μC and it is compared with a predefined wear threshold determined by means of
17 experimental characterization on the joints degradation dynamics. If the impedance is higher
18 than the predefined threshold, the joint is in good conditions (and it can safely work), whereas
19 if the impedance is lower than the predefined threshold, the joint has to be replaced. In order
20 to minimize the power consumption, the switch on the sensing circuitry has been designed to
21 be normally open (see Figure 7), thus allowing to limit the current consumption to the sensing
22 interval, i.e. when the solid state switch is closed.

1 The JS is powered with a 450mAh rechargeable Li-Poly battery. It includes a smart Power
2 Management Unit (PMU), which exploits ultra-low power Linear-Dropout regulator (LDO), i.e.
3 the TPS780270200 from Texas Instruments. This LDO has a surprisingly low quiescent current
4 of $\approx 500\text{nA}$, and efficiency higher than 85% over the whole output current range. This unit is
5 controlled by the μC , enabling advanced power management monitoring and control.

6 The JS has been developed by exploiting a hardware-software co-design approach aiming at
7 minimizing the power consumption of both hardware components and the software running
8 on the microcontroller. In fact, the only use of ultra-low power architectures do not
9 automatically allows minimizing the power consumption of the system [39], and a smart use of
10 the resources of the μC is mandatory to achieve this task.

11 The software architecture has been devised to allow the JS to exploit an ad hoc-task
12 management algorithm which plays a key role to reduce the power consumption. The
13 developed task manager defines 2 working states: i) the sleep state, where the joint is
14 assumed to be off duty, and ii) the run state, where the joint is assumed to be on duty. The
15 transition between the two states occurs if the 3-axial accelerometer detects acceleration
16 larger than 50 mg on at least one of the three axes.

17 In sleep state, we consider that the off-highway vehicle is not in use. The accelerometer is
18 not expected to measure any appreciable acceleration until the vehicle will be in use.
19 Consequently, the microcontroller and the RF transceiver are kept in sleep mode in order to
20 minimize power consumption. The only task executed in this state consists of waking up the
21 system at regular intervals to check for vibration. When the JS detects acceleration, the task
22 manager immediately switches from the sleep state to the run state.

23 In run state, the JS sends periodically a data packet containing a unique identifier of the JS, a
24 packet number, the estimated wear condition of the joint, the measured accelerations and a
25 checksum field ensuring a minimum level of consistency of the wirelessly transmitted data.

1 The checksum has been implemented in the classic hexadecimal format, and it is calculated by
2 an XOR of all characters in the message between two special characters used as delimiters of
3 the sensible data fields. The checksum is calculated by the JS, which transmits the data, and by
4 the Data Manager (DM), which receives the data. The DM checks if there is an agreement
5 between the calculated checksum and the one received from the JS. In case of agreement the
6 received data are unpacked, vice versa, the received message is discarded.

7 Interestingly, other wireless sensors can be easily realized exploiting the JS hardware
8 platform, allowing monitoring other physical parameters with minimal software overload,
9 mainly related to differences in the conditioning of the signals provided by different
10 transducers.

11
12 **Data Manager.** Figure 8 shows the simplified block diagram of the implemented DM system.
13 The core of the DM installed on the vehicle is an ARM Cortex-R4F processor, i.e. the RM48L952
14 microcontroller developed for systems from Texas Instruments. The main features of its safety
15 architecture are a dual CPU operating in lockstep, a memory with built-in self-test logic for
16 single bit error correction and double bit error detection, and a multiple inter-chip serial
17 interfaces (i.e. UART, SPI, I²C and embedded CAN controllers). The DM works as
18 communication bridge between JS and other ECUs installed on the vehicle (e.g. displays). The
19 wireless communication between DM and JS devices is implemented by means of the same
20 2.4GHz transceiver used in the JS, i.e. the CC2500 transceiver controlled using a dedicated SPI
21 bus. Of course, DM and JS devices share the same communication protocol.

22 On the other hand, the communication between DM and other ECUs installed on the vehicle
23 exploits a 250Kbps CAN communication bus. The DM device is connected to the bus through a
24 SN65HVDA541 CAN transceiver from Texas Instruments, qualified for use in automotive
25 applications.

1 Differently from the JS node, the DM device has no power consumption constraints because
2 it is powered by the main battery of the vehicle. Therefore all the voltages needed for the
3 proper internal operation of the device blocks have to be generated by its power management
4 starting from the 12V DC of the vehicle battery. Commercial DC-DC converters from Texas
5 Instruments are used to obtain a regulated voltage of 1.2V, which is required by the
6 microcontroller core, a regulated voltage of 3.3V, which is used by microcontroller peripherals
7 and CC2500 transceiver, and a regulated voltage of 5V, used by the CAN transceiver.

8 At this stage the DM has to perform tasks having a very low computational complexity,
9 hence its microcontroller is not used at its full potential. Nevertheless, it has been chosen
10 because of its internal architecture, which is specifically designed for safety critical applications
11 (i.e. its redundant architecture with dual CPU in lock-step). Furthermore, it allows
12 implementing of complex functions (e.g. working time counter, time to maintenance, graphical
13 display of all sensible parameters coming from all the sensors on the vehicle) without
14 hardware modifications.

15

16

17

1 **4. EXPERIMENTAL ASSESSMENT**

2 The performances off the ball-joint wear sensor were assessed by testing the prototypes
3 under real working conditions. Two were the aims of the experimental tests, each
4 corresponding to a step of the work: i) to choose the most appropriate coating for the wear
5 sensor; ii) to assess the system as a whole (instrumented ball joint and electronic system).

6 As described in the following, experimental tests on the coating have been carried out in
7 laboratory using an ad-hoc test bench, while the tests of the whole system have been carried
8 out installing two JS on a real tractor (one sensor on the left side of the front axle and one
9 sensor on the right side) and monitoring the wear of the two JS in real working conditions.

10

11 **4.1. Assessment of the wear monitoring ball joint**

12 The experimental assessment was performed on the prototype of the ball joint
13 implementing the wear sensor (Figure 6). The experimental campaign examined each of the
14 three types of coatings of the upper bearing described above (Rilsan, Loctite Nordbak 7227,
15 and anodic oxidation on an aluminum bearing). In order to speed up the wearing of the ball
16 joint, thus shortening the tests, only a minimum amount of lubricant was introduced inside the
17 prototype and the polyurethane sleeve was removed. This condition emulates the damage of
18 the polyurethane sleeve on the field, where only a small amount of Molykote stays inside the
19 joint. The normal lubrication condition was not examined, since, according to previous tests
20 performed by the industrial Partner, until the joint is properly sealed and lubricated, failure is
21 completely prevented.

22 The sensor was monitored through a data acquisition module (USB 6251 from National
23 Instruments [41]) which measured the electric resistance and registered the number of cycles
24 up to failure. The failure of the system was assumed to occur when the impedance between
25 the upper bearing and the external frame of the ball joint dropped down to 50% of the initial

1 value. Three replicates were performed for each type of coating, and the ball joint was tested
2 up to failure.

3 The test procedure aims to reproduce the fatigue loading which affect the ball joint in real
4 working conditions. According to the proprietary standard from Ognibene, the test bench has
5 to mimic the same geometry and kinematics of the front axle of a tractor, in order to describe
6 the typical motion law occurring in service conditions. The cycles are performed at a frequency
7 equal to 0.2 Hz, by controlling the force. The load on the joint equals 70% of the maximum
8 shear force for the ball joint along the stroke, while reaches 100% of the maximum shear force
9 at the end of stroke. The tests were performed through the ad-hoc hydraulic testing machine
10 available in the Ognibene research lab (Figure 9). This test bench reproduces on the ball joint
11 the motion law and forces prescribed by the company standard, which was inspired by the
12 Japanese automotive standard (JASO-C615-89) [39]. Thanks to a peculiar kinematic link, the
13 ball-ended pin axis sweeps a conical surface during each cycle, with an opening angle of 20°.
14 This motion law is obtained by combining the alternate translation of the piston rod (A in
15 Figure 9) which rotates on the hinge C, to the cyclic rotation of the bracket connected to the
16 hydraulic brake simulating the wheel spindle (B, in Figure 9), inclined with respect to the hinge
17 C. The test machine is equipped with a 25 kN load cell installed along the axis of the piston and
18 is supplied by an 11 kW hydraulic power unit. The whole system is controlled through a
19 hardware in the loop program developed in Labview [41].

20 Figure 10 shows in detail the combination of the motion law and the loading cycle applied to
21 the system in the experimental tests, which originate a maximum shear force on the ball-
22 ended pin of the joint up to about 16 kN.

23

24 **4.2. Assessment of the mechatronic system prototype**

1 A Landini Power Mondial 120 tractor [42] was used for the validation of the prototype in real
2 working scenarios. Figure 11 shows a prototype of the ball joint including the JS enclosed in
3 the rapid prototyped white ABS box. On each connection of the front axle of the tractor with
4 the wheel spindles, we installed a prototype, including an aluminum bearing with anodic
5 oxidation. Both wear sensors were managed by the DM device installed in the cabin.

6 In order to assess the system response, the endurance test was performed in a test track at
7 Ognibene site, including rough terrain conditions. To speed up the test, both ball joints were
8 assembled without Molikote lubricating grease, and the test lasts until worn out of both joints
9 occurred.

10 The DM collected the data received from the Joint Sensors. In normal working conditions,
11 the collected data are forwarded via CAN bus to the other vehicle ECUs, but for the specific
12 test presented in this paper the firmware of the DM has been slightly modified in order to
13 forward the collected data also through a classic serial UART communication (9600bps, 8-N-1).
14 By connecting a laptop to the DM, it has been possible to sniff the collected data and visualize
15 the associated information by means of a terminal emulator.

16 The JS awakes periodically (30 s of sampling time) from its ultra-low power consumption
17 mode to check for vibrations and measuring the correspondent accelerations along each of its
18 three physical axes. If at least one component results higher than a defined threshold (i.e.
19 50mg), the JS is considered on duty, the sensing circuitry is enabled, the wear level of the joint
20 (i.e. the joint impedance) is measured, and the relative estimated condition is sent wirelessly
21 to the DM together with the measured x-, y-, z- accelerations.

22

1 **5. RESULTS AND DISCUSSION**

2 **5.1. Assessment of the wear monitoring ball joint**

3 Table 4 collects the average number of cycles up to failure for each type of coating. At the
4 end of each test, the ball joint was disassembled and the coated bearings carefully examined
5 (Figure 12). From this visual examination it appeared that the lack of lubricant had produced
6 damaging of coating and hence a drop down of electric resistance occurred.

7 With regard to the different types of coatings, all of them provide a good wear resistance
8 before failure, but with regard to manufacturing, the Rilsan coating and the anodic oxidation
9 are easier to be produced.

10 Since the tests were performed according to the Ognibene company procedure, even though
11 they are compatible with the Japanese standard [39], they are specific for agricultural
12 equipment, the core business of the company, and it is not possible to compare these results
13 against data available from the literature. However, the main aim of these tests is to compare
14 the wear resistance of the three different coatings here examined, in order to identify the
15 more durable and reliable.

16

17 **5.2. Assessment of the mechatronic system prototype**

18 The terminal emulator used to visualize the data collected by the DM gives many
19 information. The first message informs about the DM status and its proper operation. If within
20 30 seconds no sensors send their data packet the DM notifies that there are no JS or other kind
21 of sensors installed on the vehicle on duty (second message). Vice versa when the installed
22 Joint sensors are on duty the DM processes the received data and forwards them via UART.

23 The data packet transmitted on the UART is comprised of (in order of appearance): an
24 header, the unique identifier of the JS, the packet number, the measured x- y- and z-
25 components of the accelerations (expressed in mg) and the estimated wear condition of the

1 joint. Only data packet received correctly are displayed on the terminal emulator. The
2 checksum calculated by the DM to verify the consistency of the wirelessly received data packet
3 is not included in the UART data packet.

4 Once the JS device detects an excessive wear of the joint where it is installed, the failure is
5 notified by the change in the last field of the UART data packet.

6 Field tests showed that both ball joints installed on the front axis wheel without lubricating
7 grease gave a failure message to the managing software. Disassembly of the joints highlighted
8 that this message, as expected, occurred due to worn out of the insulating alumina layer on
9 the upper conical bearing.

10 The validation test on the prototype proves that this concept of wear sensor is a simple and
11 reliable system to monitor the wear of the ball joint. Thanks to its ultra-low power
12 consumption ($\approx 5\mu\text{A}$ in sleep mode), the JS can be made autonomous through an energy
13 harvesting device, able to gather energy from the natural vibrations of the front axle occurring
14 when the machine is on duty.

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1 **6. CONCLUSIONS**

2 The work presented the development and validation of an innovative ball joint wear sensor
3 for monitoring and diagnostic of off-highway vehicles. This kind of sensor is not currently
4 available in the market and has very innovative features like: ultra-low power consumption
5 that enables self-powering through energy harvesting, wireless connectivity, small size, low-
6 cost and easy integration in existing ball joints. The ball joint wear sensor enables an active
7 monitoring of wear and damaging, thus enhancing safety, reliability and efficiency of off-
8 highway vehicles. In fact, the sensor was developed to monitor the wear in a safety-critical ball
9 joint, which connect the steering actuator and the wheel spindle, but is potentially applicable
10 to many kind of ball joints. The work presented the conceptual design and development both
11 of the mechanical and electronic system for sensor management. The assessment of a sensor
12 prototype on an agricultural tractor proved that the sensor is a simple and reliable system for
13 wear monitoring, able to diagnose incoming failure that would cause a complete loss of the
14 steering action. The ultra-low power consumption of the joint sensor make possible to develop
15 an autonomous system by including an energy harvesting device able to gather energy from
16 the natural vibration occurring on the joint when on duty.

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18

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21 Ognibene Power S.p.A. for its kind cooperation

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1 **FIGURES AND TABLES**

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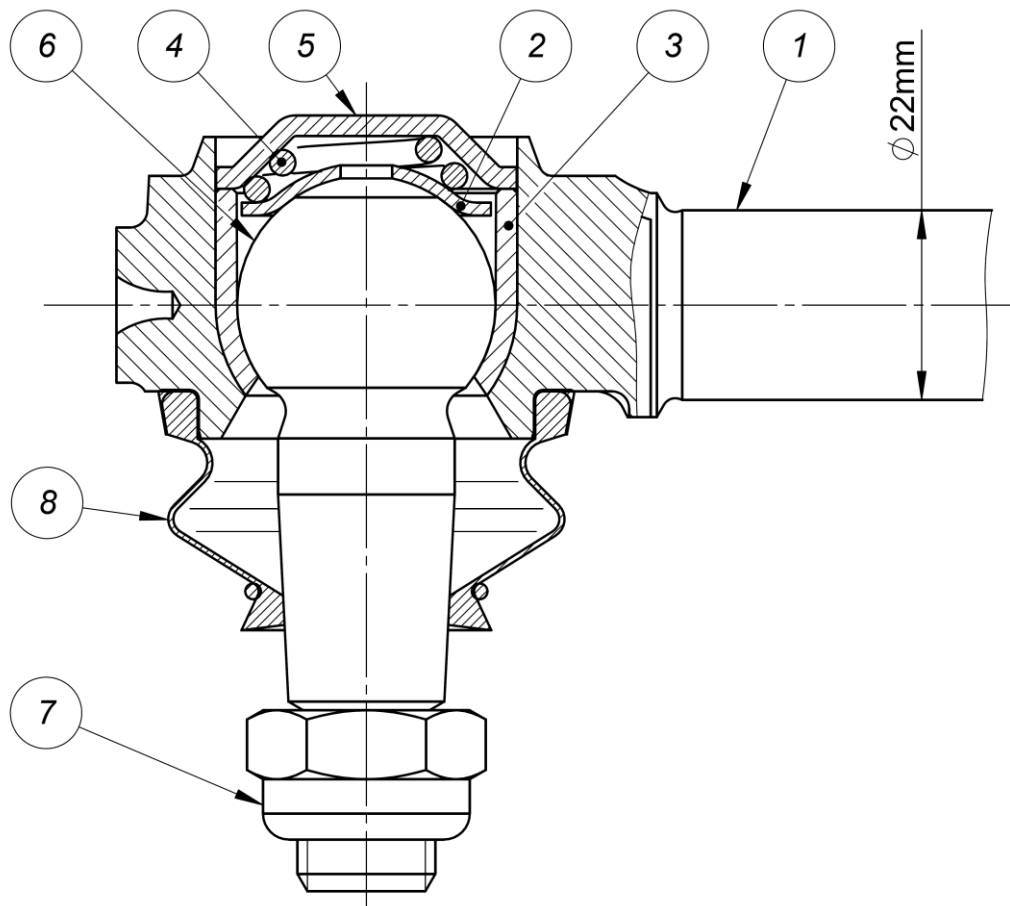
10 **Figure 1.** Ball joint at the end of an endurance test performed without lubricating grease. The
11 arrow highlights the completely failed conical upper bearing.

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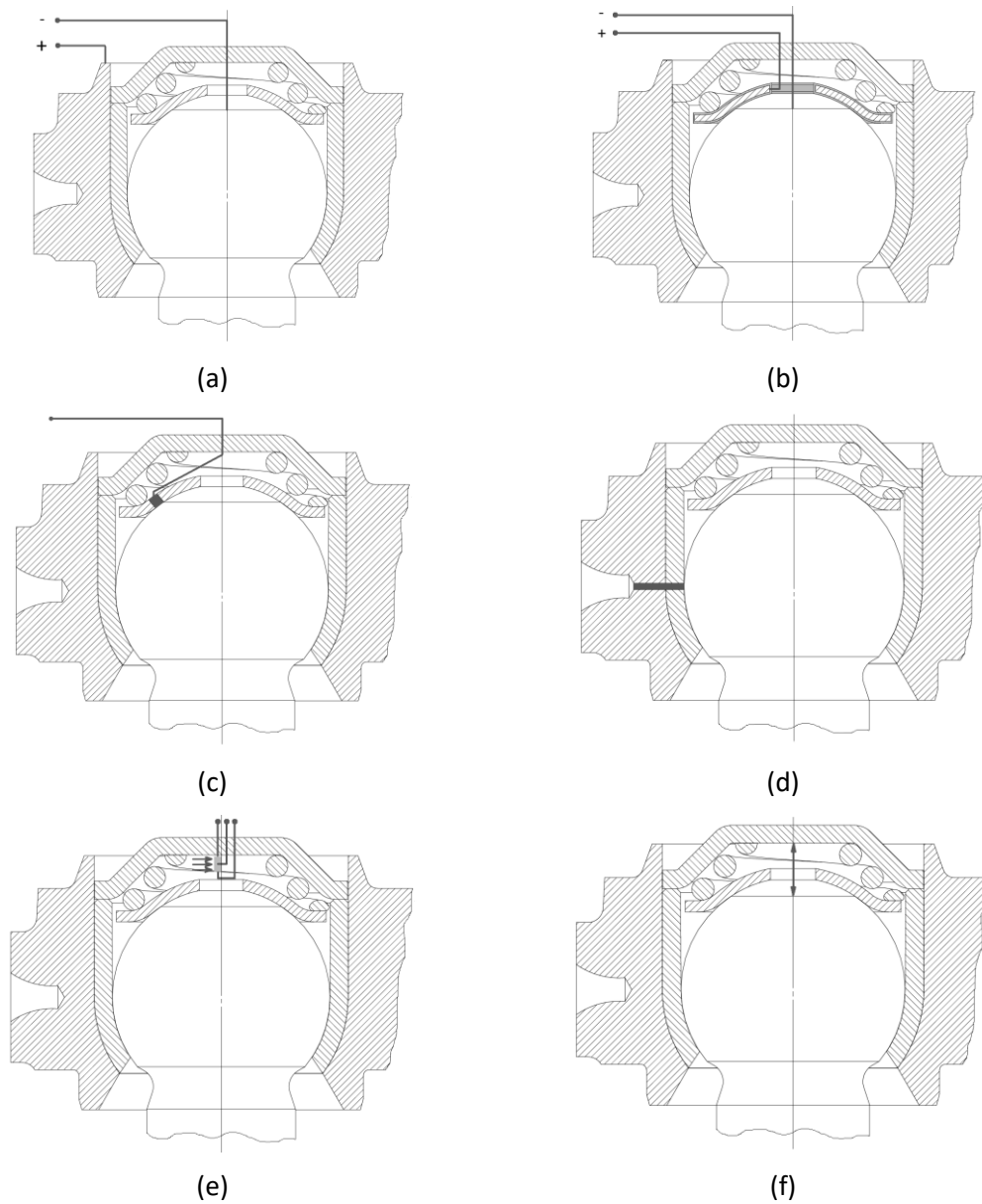
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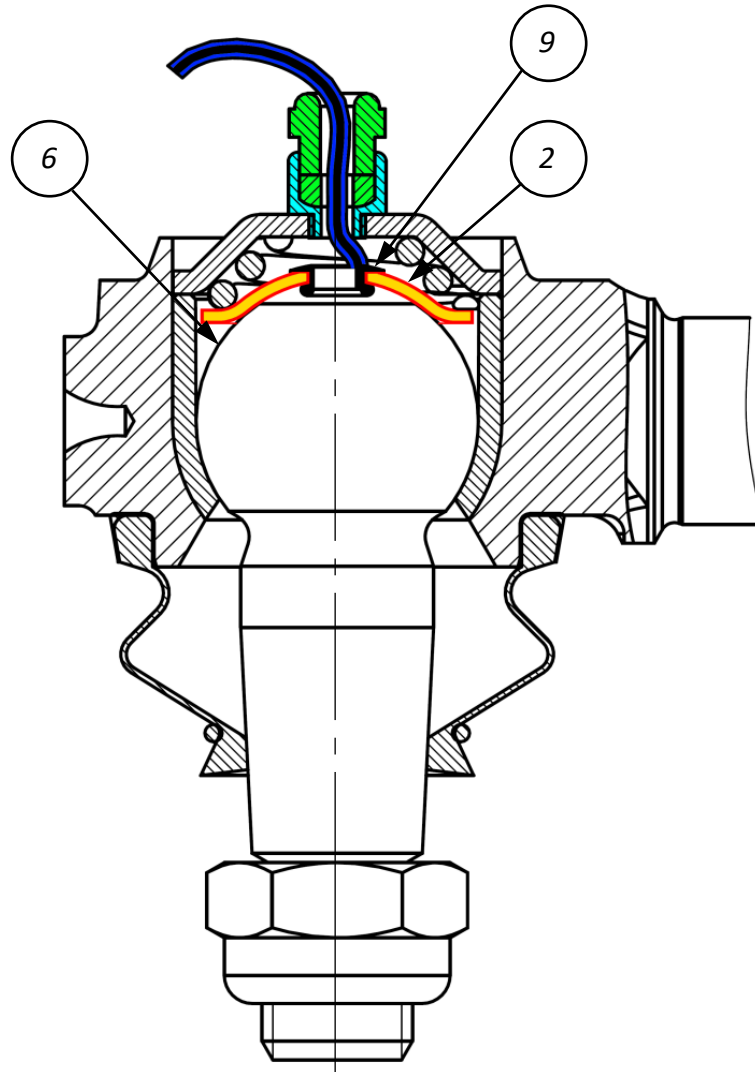
Figure 2. Sketch of the ball joint: (1) piston rod, (2) upper bearing, (3) lower bearing, (4) helical spring, (5) upper cup, (6) ball-ended pin, (7) plastic-stop nut, (8) polyurethane sleeve



1 **Figure 3.** Sensor concepts generation: (a) closed circuit between lower bearing and ball-ended
 2 pin; (b) open circuit between upper bearing and ball; (c) wearable sensing circuit embedded in
 3 the upper bearing, normally closed circuit; (d) wearable sensing circuit embedded in the outer
 4 case, normally closed circuit; (e) magnetic permeability sensor to measure the lack of lubricant
 5 inside the room of the ball joint; (f) displacement transducer to measure the relative
 6 displacement between the ball and the upper cup

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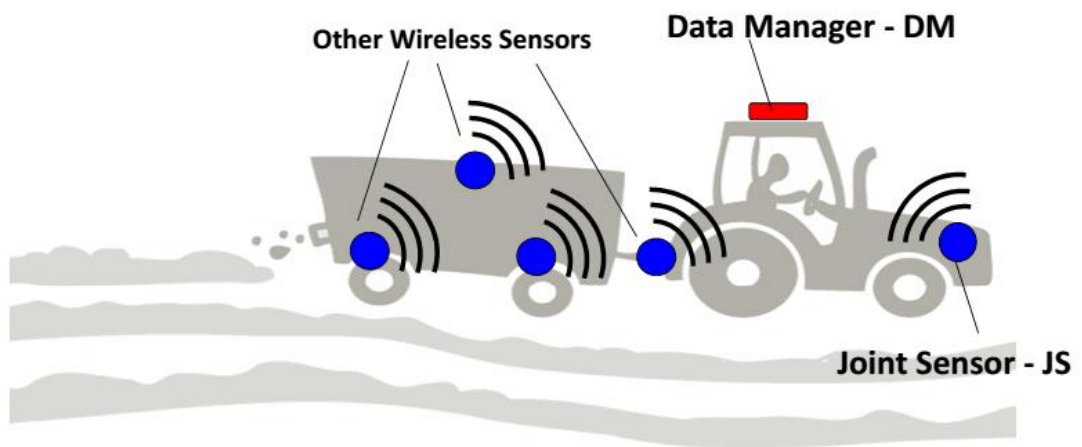
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Figure 4. Section view of the wear sensor included in the ball joint

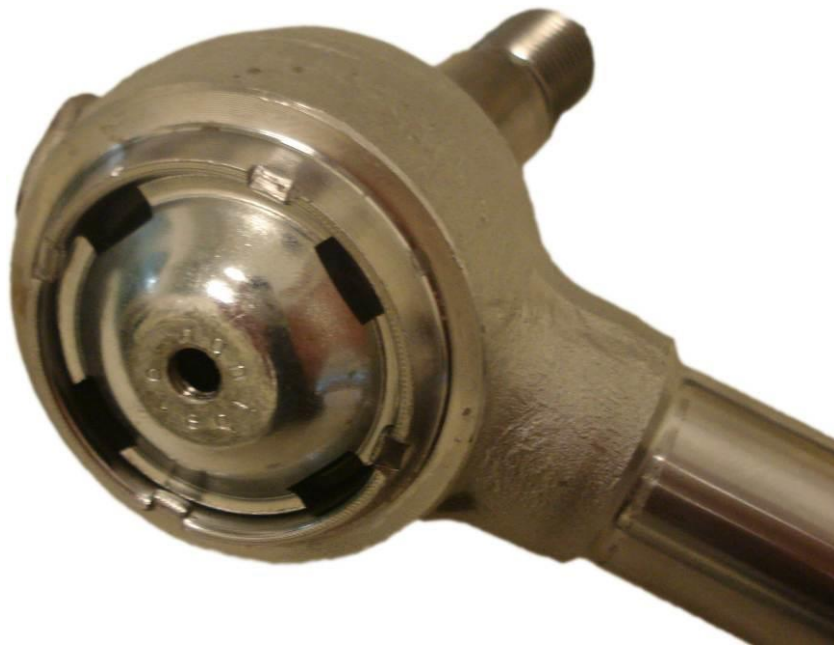
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Figure 5 System Architecture

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Figure 6. Prototype of the ball joint including the wear sensor

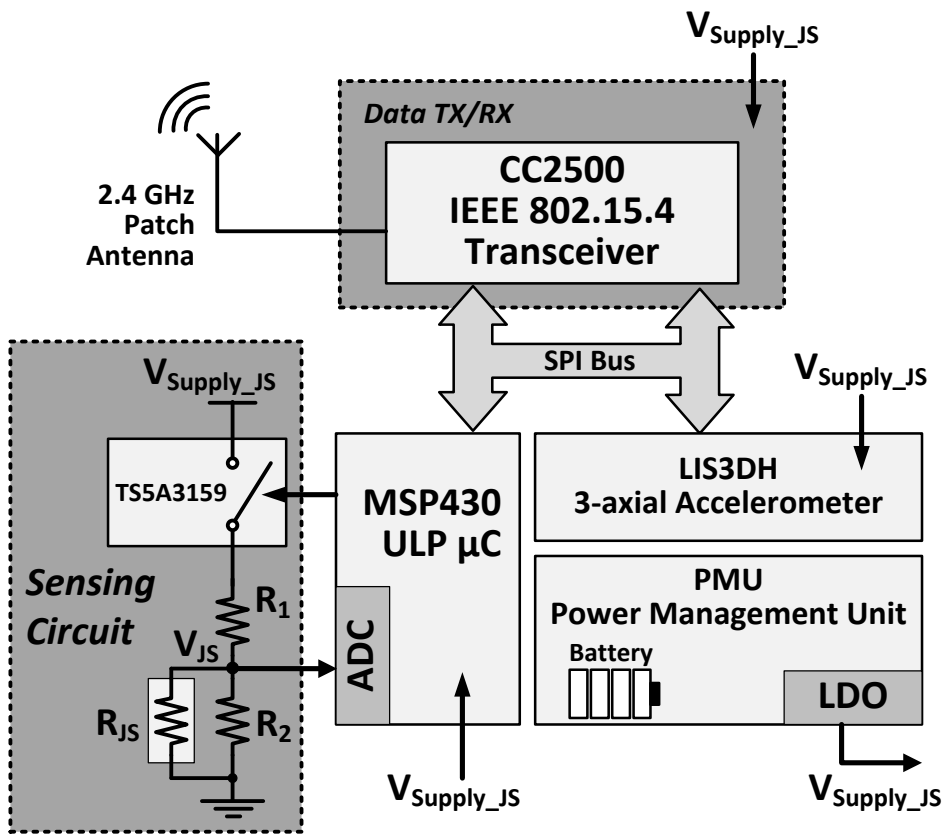


Figure 7 Simplified Block Diagram of the Joint Sensor Device - JS

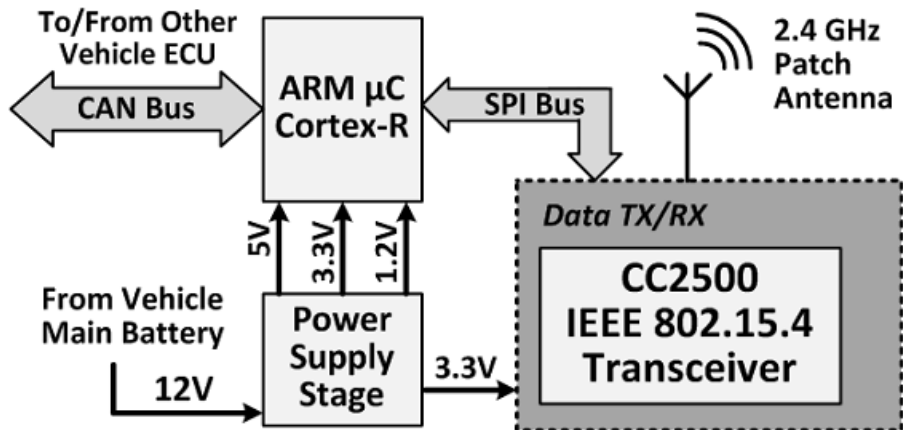
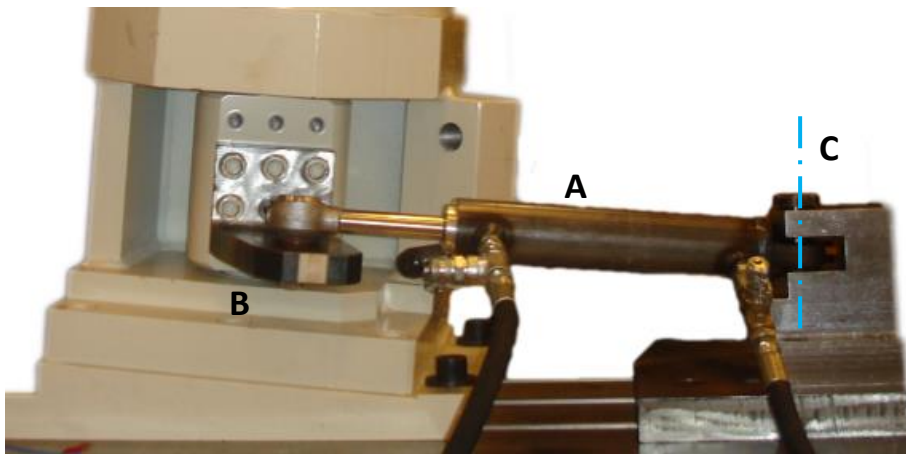


Figure 8 Simplified Block Diagram of the Data Manager Device - DM

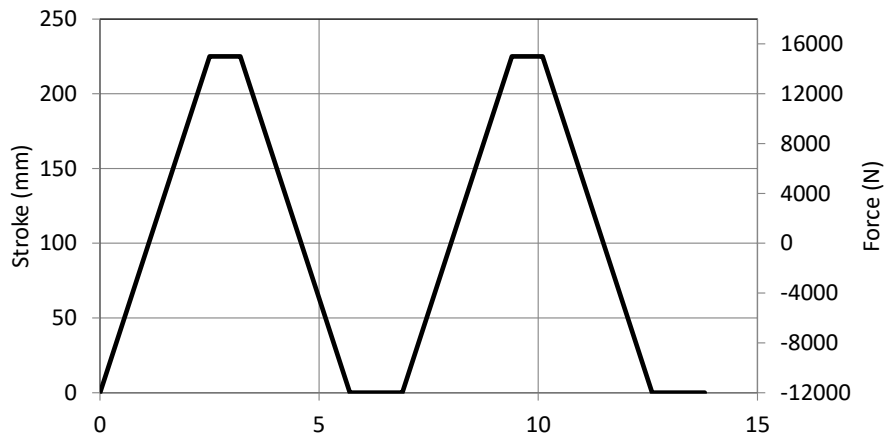
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Figure 9. Testing equipment for the ball joint wear sensor

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Figure 10. Motion law on the steering actuator during the test

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Figure 11. Prototype of the ball joint including the wear sensor and the electronic board encapsulated in a plastic case, installed on the test tractor

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(a)



(b)



(c)

Figure 12. Failed upper bearing coated with Rilsan (a), Loctite Nordbak 7227 (b), and anodized aluminum (c).

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Table 1. Technical specifications of the ball joint wear sensor

Need n°	Need	Weights	Technical specification	Unit	Value
1	Low consumption	5	Power	μW	< 100
2	Monitors wearing	5	Monitors wearing	Binary	Yes/No
3	Low cost	5	Cost	€	< 20
4	Automatic	3	Automatic	Binary	Yes/No
5	Can be implemented on different ball joints	3	Can be implemented on different ball joints	Binary	Yes/No
6	Predicts life	2	Predicts life	Binary	Yes/No
			Error in life prediction	Weeks	< 4
7	Robust	2	Max vibrations (PSD)	g ² /Hz	0.2
			Average life	Cycles	> 150000
			IP level	IP	> 56
			Operating temperature interval	°C	-35 ÷ +90
			Shock load resistance	Binary	Yes/No
8	Uses commercial components	2	Uses commercial components	Binary	Yes/No
9	Small size	1	Volume	mm ³	<4000
			Main side length	mm	< 30

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Table 2. Physical and mechanical properties of Rilsan

Melting point (°C)	Wear resistance (ASTM D4060-14) (mg)	Hardness (ASTM D2240-05) (Shore D)	Thickness (mm)	Yield strength (ASTM D638) (MPa)
186	15	75	0.2 ÷ 0.5	40

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Table 3. Physical and mechanical properties of Loctite Nordbak 7227

Operating temperature (°C)	Compression strength (ISO 604) (MPa)	Lap shear strength (ISO 4587) (MPa)	Hardness (ASTM D2240-05) (Shore D)
-30 ÷ +95	86.2	13.8	85

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Table 4. Results from the experimental tests

Coating type	Average number of cycles before failure
Rilsan	22925
Loctite Nordbak 7227	14321
Anodic oxidation	35260

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