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FUNCTIONAL SAFETY OF THE HYDRAULIC DRIVE CONTROL SYSTEM OF A TRACKED UNDERCARRIAGE

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Abstract

In the study, the functional safety of the hydraulic drive control system of a tracked undercarriage used as a mobile platform for a robotic bricklaying system (RBS) was evaluated. Hazards and risks caused by the hydraulic drive control system of the rubber track undercarriage were identified. The schematic diagram and main components of the conventional hydraulic drive control system of a tracked undercarriage are presented. The functions and parameters of the components of the hydraulic power and control system are discussed. In a conventional hydraulic drive, the safety function is fulfilled by failsafe brakes built into the hydraulic motors. To ensure that the RBS works safely on the construction site, it was necessary to introduce an advanced safe control system for the hydraulic drive of the tracked undercarriage. An advanced safe control system for the hydraulic drive of the tracked undercarriage includes hydraulic control valves with safety functions, a category 3 safe two-channel control architecture, and a safety microcontroller. SISTEMA software tools were utilized to determine safety functions and calculate their specifications. Based on the specifications of the safety function associated with the category of safety control architecture, the achievable performance level of the hydraulic drive control system for the tracked chassis was determined.

Keywords: functional safety; performance level; tracked undercarriage; control system; hydraulic drive

1. Introduction

The automotive sector encompasses a variety of activities related to the manufacture, design, development, manufacturing, marketing, sales, repairing, and modifying of motor vehicles. A motor vehicle with a tracked undercarriage/chassis reduces load pressure transferred to the ground and improves off-road performance. Tracked undercarriages have

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petrol, diesel or electric (AC/DC) power packs and optional remote-controlled hydraulic and electronic systems. A hybrid mobile application consists of a number of different types of locomotion mechanisms, such as track-wheels, etc. As with all other vehicles, the dimensions of the tracked undercarriage can be adapted to meet individual needs. The tracked undercarriage may have a large ground clearance, allowing the vehicle to overcome obstacles such as rocks and debris. The skid-steer tracked vehicle is suitable for rough agricultural and industrial applications. Industrial robots are essential for modern manufacturing in the automotive industry. Industrial robots placed on mobile tracked platforms can perform various specialized production tasks. Tracked machines are used in the automotive industry, car repair plants, collision centres, car parks, etc. The tow track moves on a tracked undercarriage by remote control and can go into tight, cramped parking areas or low clearance garages. The tracked towing machine solves international problems related to towing and transporting vehicles. Tracked machines are the ideal solution to move vehicles up to 4 tons on flat surfaces such as asphalt, car parks, warehouses and body shops with concrete or resin floors. Electric tracked machines can handle road vehicles up to 2.2 tons. The main focus of [6] was on the analysis and control of an articulated track vehicle. Articulated tracked vehicles are appreciated for their extreme maneuverability, mobility flexibility, and slope and side slope capabilities. Tracked vehicles are more advantageous than wheeled vehicles due to their stable movement on loose and uneven terrain [11]. The behaviour of tracked vehicles when cornering has special characteristics that differ significantly from that of wheeled vehicles [3]. In [8] an analytical framework is presented to predict the distribution of ground pressure and the tractive performance of tracked vehicles. In [9], a general theory is presented for the skid steering of tracked vehicles under steady state conditions on firm ground, taking into account the shear stress-shear displacement relationship at the track-ground interface.

Tracked vehicles, machines, and equipment are becoming more and more popular because they can operate on a variety of surfaces. Tracks travel smoothly on the surface because they distribute even pressure on the ground. Rubber track machines are often used in the agricultural sector, in construction, and in industry. Rubber tracks allow the use of a tracked undercarriage inside and outside, and its load capacity can be increased. Due to their low soil pressure, rubber tracks are suitable for virtually all subsoils. Rubber tracks leave almost no tracks in the subsoil and do not damage it. A tracked undercarriage with rubber tracks is stable in all subsoils. Rubber tracks are highly manoeuvrable and stable, which guarantees efficient and safe work. The vibration levels of the rubber tracks are significantly lower than those of other similar tracks. As a result, there is less wear on the entire machine, particularly the rollers, idlers, and sprockets. This leads to less machine downtime and lower maintenance costs. Additionally, this will provide the operator with greater comfort. When assessing the risk of controlling the hydraulic drive of a tracked undercarriage, it is necessary to take into account not only the power and pressure of hydraulic system, but also the movement of the tracks. Due to their larger surface area, tracked machines can handle inclines and rough sites. The safe operation of the tracked undercarriage requires following recommended rules, such as avoiding reverse operation, avoiding constantly turning to the right or left,

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avoiding unnecessary speeds, avoiding too deep spinning tracks, avoiding wide track shoes, avoiding track impacts, wise use of track counterrotation, carefully planning work that affects undercarriage wear, proper storage and parking of the undercarriage, and applying appropriate maintenance processes.

Occupational safety is of key importance when using mobile machines with tracks. If not used properly, tracked machines can become dangerous. To maintain a safe workplace and improve working conditions with tracked undercarriage, appropriate safety measures must be followed and applied. Organizing a safe workplace involves eliminating hazards or replacing them with less dangerous ones. If threats cannot be eliminated, then the main goal should be to implement a risk assessment to prevent or at least reduce them. Appropriate steps should be taken to reduce the potential risks of using a tracked undercarriage. Working safely with tracked undercarriages is not a matter that should be taken lightly. By following safe procedures, one can protect tracked undercarriage operators, ground workers, and other bystanders.

Vehicles, machines and equipment operations on construction sites can cause a lot of serious injuries and fatalities [4, 5, 7]. According to [2], tilt stability monitoring systems on-board can greatly improve the operational safety of tracked machines. In [10], a steering stability control method is proposed for a high-speed tracked vehicle with a four-motor distributed drive to improve handling stability and safety. In the construction of tracked machines, functional safety control systems help to cover the requirements of health and safety protection according to Machinery Directive 2006/42/EC. The starting point here is the risk analysis and risk estimation based on EN ISO 12100. This standard describes fundamental hazards and helps the designer identify relevant and significant hazards that are reduced to an acceptable residual risk through risk reduction measures. Functional safety, according to the EN ISO 13849 standard, is the term used when safety depends on the correct function of a control system. Risk assessment plays a central role with respect to functional safety requirements. The functional safety of the hydraulic drive control system of the tracked undercarriage must be designed so that the safe state is one of the depowering of hydraulic motors. Then all dangerous movements of the tracked undercarriage will be stopped, i.e., stopping is a safe state.

2. Tracked undercarriage for the build-up of RBS

The conventional hydraulically driven Hinowa PT20GL rubber track undercarriage with 5 + 5 rollers was chosen for mobile RBS. Figure 1 shows a view of the Hinowa tracked undercarriage as a mobile platform for the built-up of RBS. Mobile RBS was created as part of a research project in cooperation between Kielce University of Technology as the leading researcher, the CBRTP research and development partner, and the STRABAG industry partner [1]. The mobile RBS build-up on a Hinowa tracked undercarriage must move around the construction

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area for long distances, at the construction site for short distances, and at the bricklaying station for the precise positioning of the bricklaying robot. The Hinowa tracked undercarriage can move forward and backward at a speed of 0.56 m/s, the maximum slope of the driveway ±15°, and maximum lateral inclination ±8°.

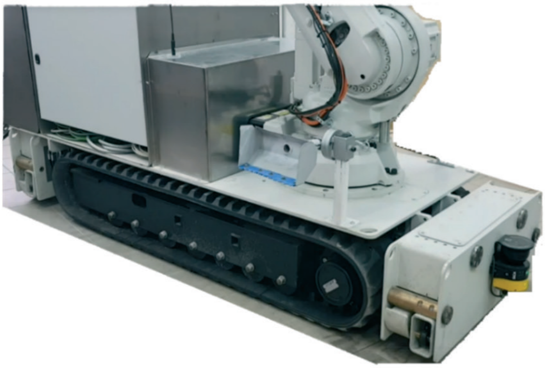

Fig. 1. View of the Hinowa tracked undercarriage as a mobile platform for the build-up of RBS [1]

The dimension specifications and payloads of the Hinowa tracked undercarriage are shown in Figure 2.

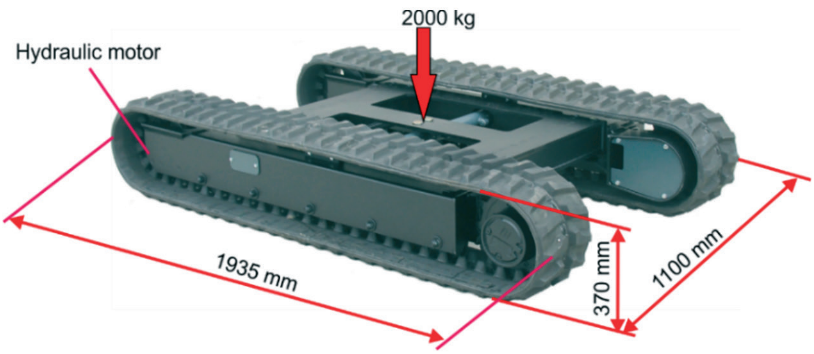

Fig. 2. Dimension specifications and payload of the Hinowa tracked undercarriage

Figure 3 shows the built-up of the tracked undercarriage, which has been patented as utility models.

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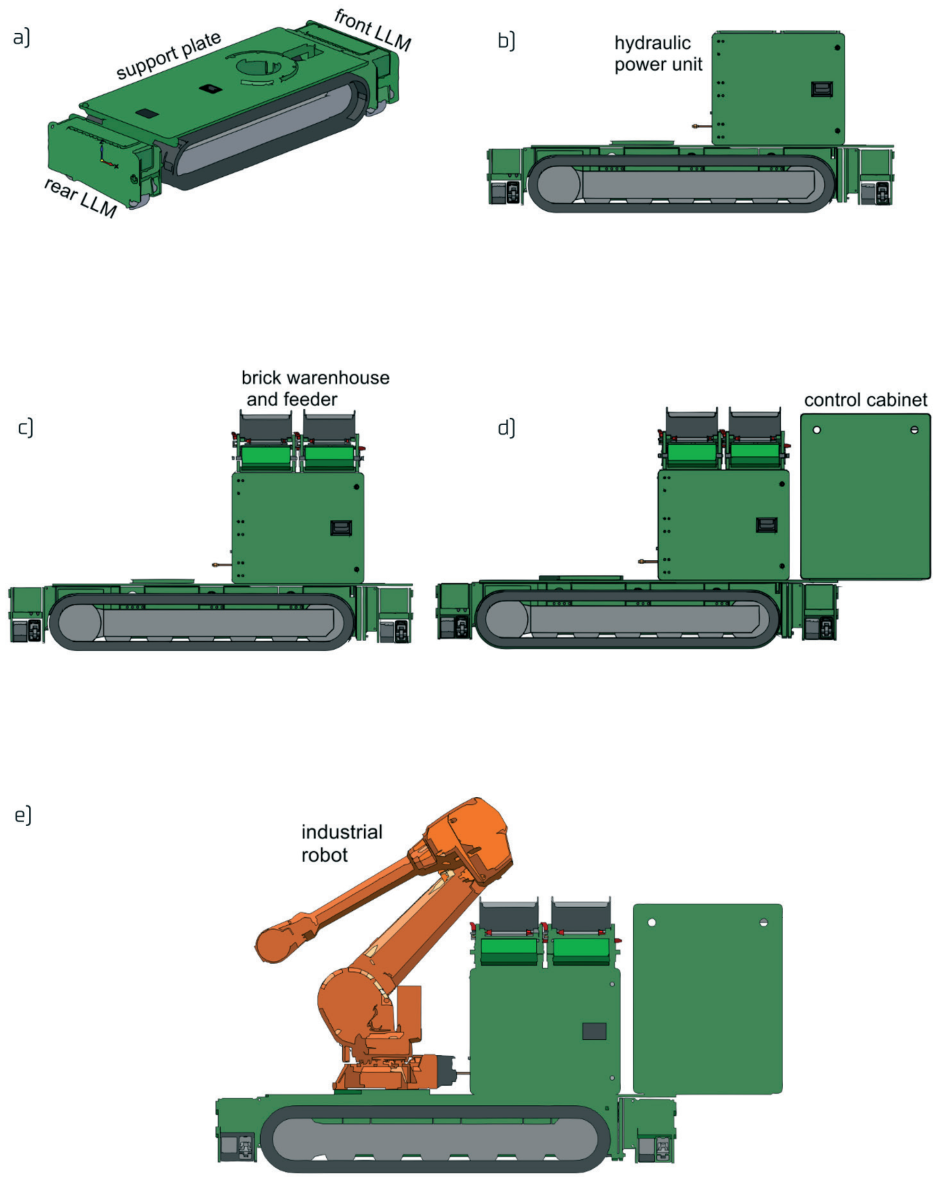

Fig. 3. Built-up tracked undercarriage: a) support plate and lifting and levelling module (LLM); b) hydraulic power unit; c) brick warehouse and feeder; d) control cabinet; e) industrial robot [1]

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The 3D CAD model of the mobile RBS is shown in Figure 4. Mobile RBS consists of an ABS six-degrees-of-freedom (6DoF) industrial robot with a replaceable hydraulic gripper, Hinowa tracked undercarriage, robot support frame, front and rear hydraulic lifting levelling module, hydraulic power and control module, brick warehouse, brick feeder, control panel, and control cabinet. The mobile ZSM enables the bricklaying of walls in large workspaces, limited by the robot's working range. The ABB industrial robot of type IRB4600 was used, with a weight of 450 kg, a maximum vertical range of 3.055 m, a maximum horizontal range of 2.55 m, and a repeatability of 0.06 mm.

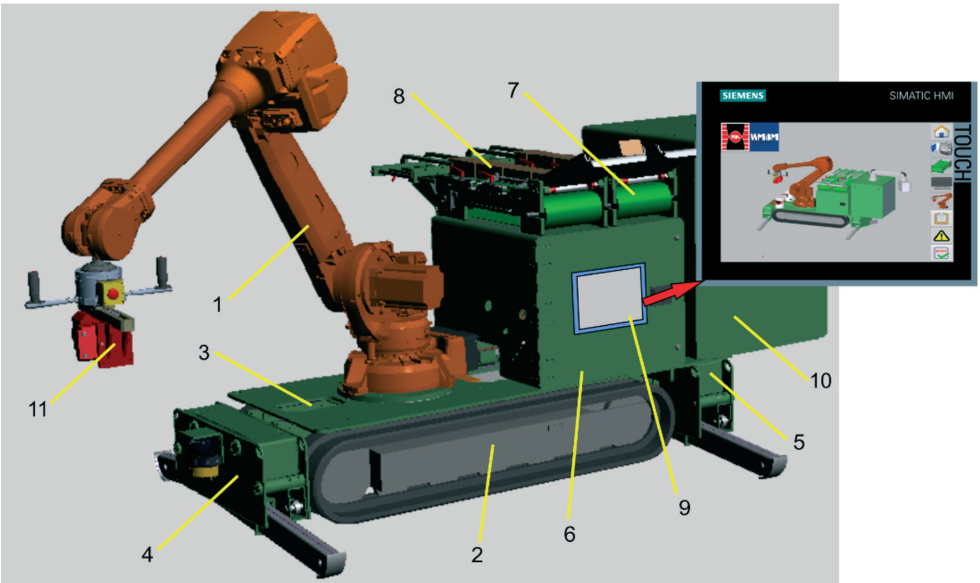

Fig. 4. 3D CAD model of a mobile RBS: 1 – ABB industrial robot; 2 – Honowa tracked undercarriage; 3 – robot support frame; 4 – front hydraulic lifting levelling module; 5 – rear hydraulic lifting levelling module; 6 – hydraulic power and control module; 7 – brick warehouse; 8 – brick feeder; 9 – control panel; 10 – control cabinet; 11 – hydraulic gripper of the robot [1]

3. Conventional hydraulic drive control system of a tracked undercarriage

Figure 5 shows a schematic diagram and the main components of the conventional hydraulic drive control system of the Hinowa rubber track undercarriage. A conventional hydraulic drive control system of a tracked undercarriage was used for the prototype version of the RBS.

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The hydraulic drive of a tracked undercarriage is powered by a hydraulic unit (HPU). The HPU includes a servo pump consisting of a Simens Simotics electric servomotor and a Hydro-Leduc fixed displacement hydraulic pump. The Siemens Simotics M 1PH8103-10002-0GA1 compact electric asynchronous servomotor was used with a nominal speed of 1500 rpm, a maximum speed of 9000 rpm, a nominal torque of 34 Nm, a maximum torque of 60 Nm, and a nominal power of 6.3 kW. The Simotics servomotor is freely configurable for specific applications due to its modular design. The Simotion servomotor control system is based on the drive control chart (DCC), which allows for variable-speed operation of the hydraulic pump. The Simotics servomotor provides an innovative and energy-efficient solution concept for hydraulic drive and control. The principle of operation of the Simatic system is to regulate the speed and torque of the servo motor to directly control the pump pressure and flow rate. As a result, hydraulic power is supplied only by the pump when it is necessary to operate the hydraulic motors of the tracked undercarriage.

The servo pump unit uses a Hydro-Leduc XPi 12 0523820 fixed displacement piston hydraulic pump with a bending axis with a geometric displacement of 12 cm^3/rev, a flow rate of 24 L/min, a maximum working pressure of 380 bar, a maximum speed of 3150 rpm, and a maximum torque of 76 Nm. Hydro Leduc XPi bidirectional pumps are specifically designed to meet the needs of mobile devices. The pump automatically starts in the required rotation direction.

The Hydac multi-sectional directional proportional valve (MSV) is the hydraulic control element of hydraulic motors to drive the tracked undercarriage. The Hydac valve LX-610/B0 with a nominal pressure of 350 bar and a nominal flow rate of 160 L/min can independently control the operating functions of the tracked undercarriage hydraulic motors. This valve ensures stable and reliable control of hydraulic motors even under higher loads. Pressure sensors are placed in the MSV to monitor the pressure in the hydraulic drive system.

The tracked undercarriage is driven by two Bravini CTM1022 hydraulic orbital gear motors of the BRZV series with a displacement of 80.4 cm^3/rev, a maximum flow of 65 L/min, a maximum pressure of 210 bar, a maximum rotational speed of 119 rpm, and a maximum torque of 1280 Nm. Hydraulic motors feature a planetary gearbox (one reduction stage) and built-in failsafe brakes. The failsafe brakes disengage upon activation of the shuttle valves when the hydraulic motors are powered, or engage upon deactivation of the shuttle valves when the hydraulic motors are not powered.

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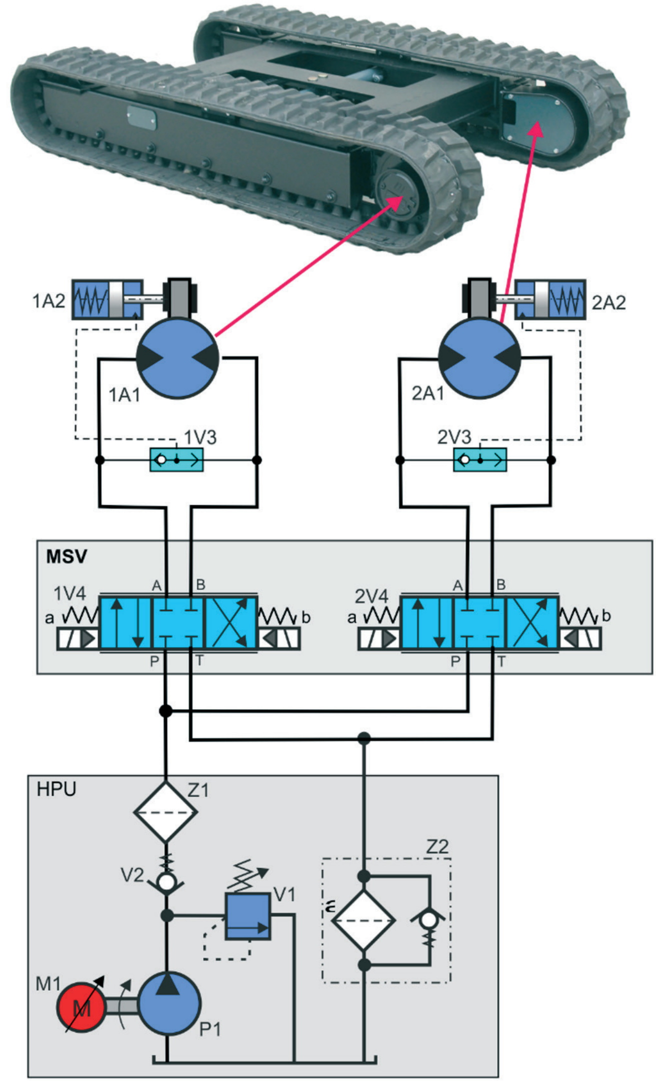

Fig. 5. Schematic diagram of the conventional hydraulic drive control system of the tracked undercarriage: HPU – hydraulic power unit: M1 – servomotor; P1 – hydraulic pump, V1 – relief valve; V2 – check valve; Z1 – high pressure filter; Z2 – low pressure filter; MSV – multi-sectional valve: 1V4 and 3V4 – proportional directional control valves; 1V3 and 2V3 – hydraulic shuttle valves; 1A1 and 2A1 – hydraulic motors, 1A2 and 2A2 – hydraulic actuators for fail-safe brakes

A programmable Simatic S7-1500 controller was used to control the hydraulic drive of the tracked undercarriage. The controllers are located in the RBS control cabinet. The controller is in constant communication with the robot control system. The control system operates

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on the Profinet communication network. The operating elements of the electrical, hydraulic, and mechanical systems are used.

The Simens Simatic HMI touch control panel with the WinCC Advanced V16 application that is developed begins to allow the operator to communicate visually with the RBS master controller. The Simatic HMI touch panel has several screens that can be called on the corresponding buttons, including to control the hydraulic drive of the tracked undercarriage. Figure 6 shows the Simatic HMI touch panel screen for hydraulic drive control of the tracked undercarriage.

Hydraulic drive control of the Hinowa tracked undercarriage is possible using a radio-controlled console. The radio-controlled console shown in Figure 7 ensures maximum safety travelling of the tracked undercarriage. The radio-controlled console includes the emergency stop button (red mushroom), which displays the selected track undercarriage operating mode, switches for the selected tracked undercarriage operating mode, and a joystick to control the tracked undercarriage tracks. Additionally, on the right side of the console there is a switch for turning the device's power on and off, and a fault reset button. On the left side of the console, there are buttons to start and stop the servo pump of the tracked undercarriage hydraulic drive. If there is a discharged battery, you can control the tracked undercarriage using the cable.

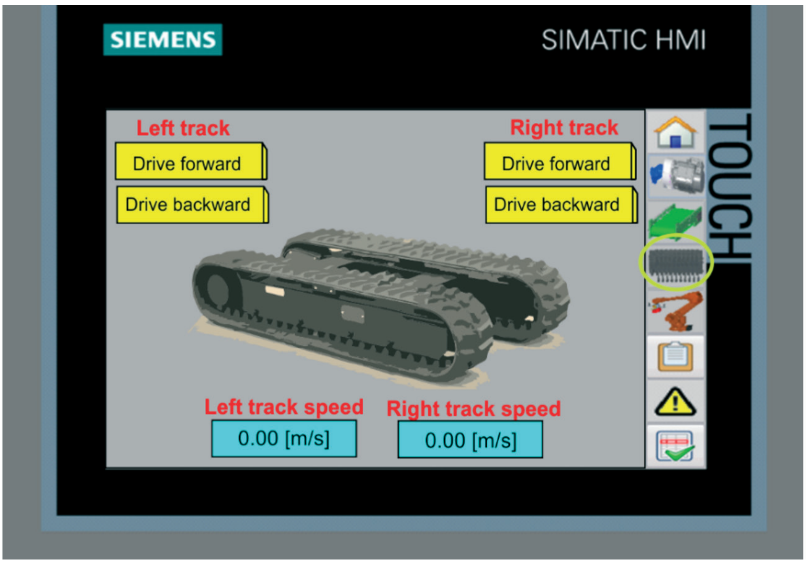

Fig. 6. HMI touch control panel screen for the hydraulic drive of the tracked undercarriage

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a)

b)

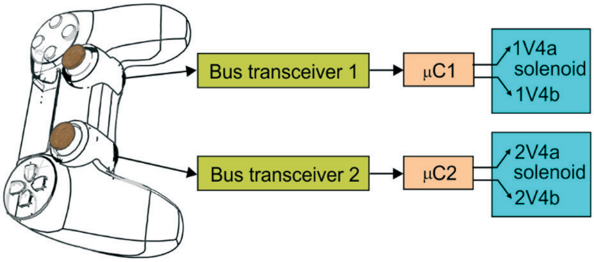

Fig. 7. Radio-controlled operator: a) operator console; b) operator control system: µC1 – microcontroller of the 1V4 valve; µC2 – microcontroller of the 2V4 valve

4. An advanced safe control system for the hydraulic drive of the tracked undercarriage

Risk and hazards are defined as a potential source of harm. In the case of a tracked undercarriage, the risk of collision may occur constantly, e.g., during movement of the tracked undercarriage; it may occur unexpectedly, e.g., risk of crushing due to unexpected activation, acceleration, or deceleration of the drive of the tracked undercarriage; it may occur accidentally, e.g., ejection or fall as a consequence of the damage to the drive of the tracked undercarriage. The Hazard Qualifier as Performance Level (PL) according to ISO 13849 can provide more information on the source of risk and hazards associated with the hydraulic drive control of the undercarriage drive, such as severity, exposure to hazardous events, the possibility of avoiding harm, awareness of the hazard, the ability to react, and controllability. PL applies to the assessment of functional safety and the level of safety performance of the hydraulic drive control systems of the tracked undercarriage.

In order for RBS to work safely on the construction site, it was necessary to introduce an advanced safe control system for the hydraulic drive of the tracked undercarriage. Figure 8 shows the advanced safe control system for hydraulic drive of the tracked undercarriage,

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which includes hydraulic control valves with safety functions, a category 3 of the safe control architecture, and a safety microcontroller.

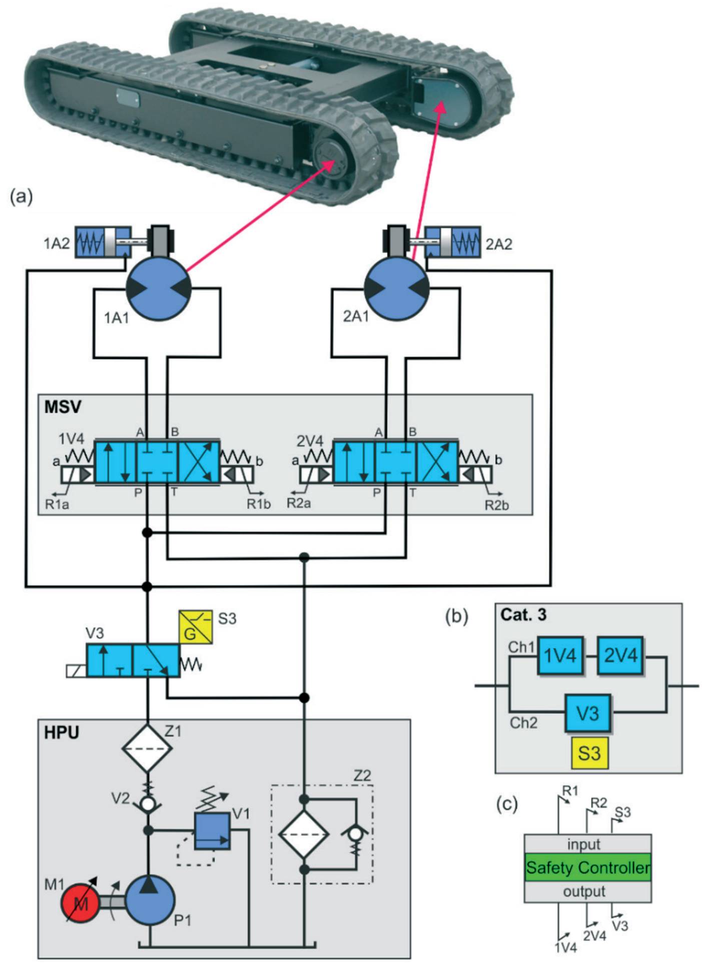

Fig. 8. Safe control system for the hydraulic drive of the tracked undercarriage: a) schematic diagram of the hydraulic drive control system of the tracked undercarriage with safety functions; b) block diagram of the safety category architecture; c) safety controller

The hydraulic drive control system of the tracked undercarriage follows the basic and proven principles of safety function (Figure 8a). Dangerous and risky movement of the tracked undercarriage, which can pose a danger to surrounding structures, results from the drive control of hydraulic motors 1A1 and 2A1 with built-in failsafe brakes activated by actuators 1A2 and 2A2. The failsafe brakes disengage when the V3 brake valve is turned on, allowing the movement

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of the hydraulic motors, or engage when the V3 brake valve is turned off, inhibiting the movement of the hydraulic motors. In the event of an emergency, the V3 brake valve activates the fail-safe brakes acting as emergency brakes. During the normal operation of the tracked undercarriage, the movements of two hydraulic motors 1A1 and 2A1 can be stopped by the two proportional directional control valves 1V4 and 2V4 or at a higher level by the directional control valve V3. Failure of one of the 1V4 or 2V4 valves alone does not result in loss of the safety function of the hydraulic drive control. The 1V4 and 2V4 valves are actuated cyclically in the control process of the hydraulic motors 1A1 and 2A1 by the microcontroller. Valve V3 closes only in response to a demand for the safety function. The technical means of fault detection in the hydraulic control system is only implemented by monitoring the position of the V3 valve by the position sensor S3. The V3 valve has a position monitoring function, since it is not cyclically switched. The safe state of the hydraulic drive control system is achieved by closing the V3 valve by turning off the electrical control signal. The 1V4 and 2V4 valves have a closed centre position with an underlap and spring centering. The positions of valves 1V4 and 2V4 are indirectly monitored by the processing of electrical signals in the microcontrollers. In the tracked undercarriage drive system, the requirements of the category 3 two-channel safe control architecture are met (Figure 8b). In channel 1, valves 1V4 and 2V4 are indirectly monitored by processing electrical signals in the safety microcontroller. In channel 2, valve V3 is directly monitored by sensor S3 in the safety microcontroller. The input and output signals of the safety microcontroller are shown in Figure 8c. Figure 9 shows a block diagram of the safe control system for the hydraulic drive of the tracked undercarriage.

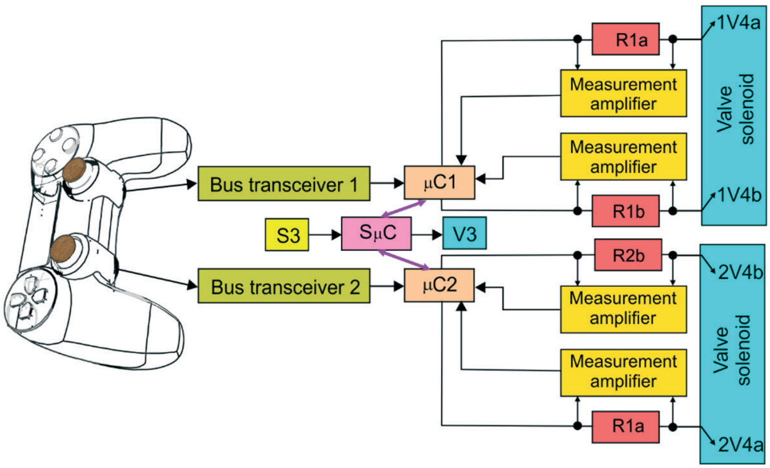

Fig. 9. Block diagram of the safe control system for the hydraulic drive of the tracked undercarriage: SμC – safety microcontroller; μC1 – microcontroller of the 1V4 valve; μC2 – microcontroller of the 2V4 valve; R1 – resistance of the 1V4valve; R2 – resistance of the 2V4 valve; S3 – position measurement of the V3 valve

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In the hydraulic drive control system of the tracked undercarriage, the valves V3, 1V4, and 2V4, perform the tasks related to safe control, therefore, they are assessed in terms of the safety performance PL. The required safety functions are achieved thanks to the failsafe brakes of the 1A1 and 2A1 hydraulic motors. To determine PL, one can use the SISTEMA software tools developed at the Institute for Occupational Safety and Health of the German Social Accident Insurance. The SISTEMA software tools provide users with comprehensive support to evaluate the safety of the hydraulic control drive of a tracked undercarriage according to the ISO 13849-1 standard. The value of the required performance level (PLr) of the hydraulic drive control system of the tracked undercarriage was determined on the basis of the risk graph presented in Figure 10. The risk graph shows that the value of the required safety level is PLr = d.

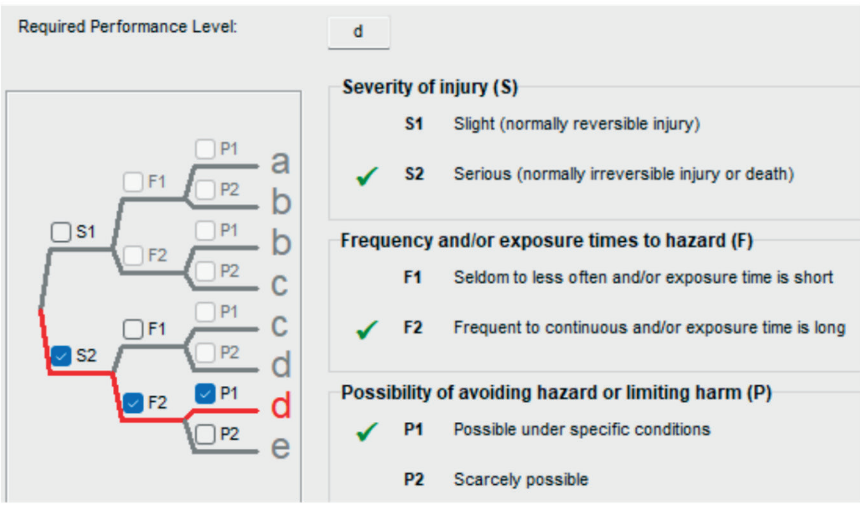

Fig. 10. Determine the value of the required performance level *PLr* from the risk graph

The step-by-step SISTEMA software defines the relevant parameters for assessing the control safety of the hydraulic drive of the tracked undercarriage, such as category architecture (*Cat.*), the mean time to dangerous failure (*MTTFd*), measures against common-cause failures (*CCF*) in multichannel systems, average diagnostic coverage (*DCavg*) of hydraulic components (valves), and the average probability of dangerous failure per hour (*PFHd*). These parameters ultimately determine the performance level (PL) of the hydraulic drive control system. Figure 11 shows the SYSTEM software window, which shows the parameters used to assess the PL value of the hydraulic drive control of the tracked undercarriage.

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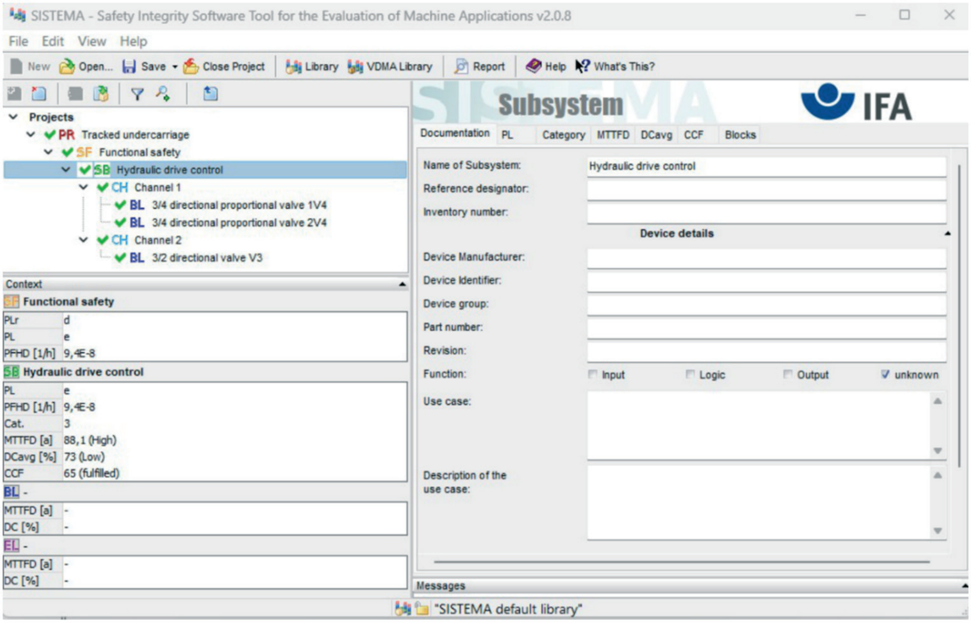

Fig. 11. SYSTEM software window

The method of calculating the symmetrized $MTTFd$ value and the average DC value for channels 1 and 2 in SISTEMA is as follows.

In channel 1, for valves 1V4 and 2V4, the value of $MTTFd(_{\mathrm{Ch1}})$ is assumed to be 150 years, then

$$MTTFd_{(Ch1)} = \frac{1}{\dfrac{1}{MTTFd_{(1V4)}} + \dfrac{1}{MTTFd_{(2V4)}}} = \frac{1}{\dfrac{1}{150} + \dfrac{1}{150}} = 75 \text{ years}$$

In channel 2, for valve V3, the value of $MTTFd(_{\mathrm{Ch2}})$ is assumed to be 150 years, which is limited to a maximum value of 100 years.

A symmetrized $MTTFd$ value is calculated as follows,

$$MTTFd = \frac{2}{3}\left[MTTFd_{(Ch1)} + MTTFd_{(Ch2)} - \frac{1}{\dfrac{1}{MTTFd_{(Ch1)}} + \dfrac{1}{MTTFd_{(Ch2)}}} \right] =$$

$$= \frac{2}{3}\left[100 + 75 - \frac{1}{\dfrac{1}{100} + \dfrac{1}{75}} \right] = \frac{2}{3}[175 - 43] \approx 88.1 \text{ years}$$

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A symmetrized $MTTFd$ value of 88.1 years is high.

For the valve V3, the DC value is 99%.

For the 1V4 and 2V4 valves, the DC values are 60%.

The averaging of DC gives the following

$$DC_{avg} = \frac{\frac{DC_{(V3)}}{MTTFd_{(V3)}} + \frac{DC_{(1V4)}}{MTTFd_{(1V4)}} + \frac{DC_{(2V4)}}{MTTFd_{(2V4)}}}{\frac{1}{MTTFd_{(V3)}} + \frac{1}{MTTFd_{(1V4)}} + \frac{1}{MTTFd_{(2V4)}}} = \frac{\frac{0.99}{150} + \frac{0.60}{150} + \frac{0.60}{150}}{\frac{1}{150} + \frac{1}{150} + \frac{1}{150}} = \frac{0,0146}{0,02} = 73\%$$

The average $DCavg$ value of 73% is low.

The combination of the three hydraulic control elements (valves) corresponds to Category 3 with a high $MTTFd$ (88.1 years), low DCavg (73%), and a fulfilled CCF (65 points: separation 15, overvoltage protection 15 and environmental conditions 35). This results in an average probability of dangerous failure of $PFHd = 9.35 \times 10\text{-}8$ per hour.

Based on these parameters, the value of the performance level PL = e was determined. The performance level is satisfied for the safety control system for the hydraulic drive of the tracked undercarriage, because $\mathrm{PL} = \mathrm{e} \geq \mathrm{PLr} = \mathrm{d}$.

5. Conclusions

The solution of the functional safety issue of the hydraulic drive control system of the tracked undercarriage requires the identification of the hazard and the estimation of the risk. Failure or damage to the control system for the hydraulic drive of the tracked undercarriage can pose a danger to the surroundings. Hazards and risks depend on the speed of travel of the tracked undercarriage. At different speeds of the tracked undercarriage, the safe control function should be maintained. Failure to meet the guaranteed requirements for safe control of the tracked undercarriage can be an indirect risk source.

Due to the identified danger posed by the tracked undercarriage with RBS travelling around the construction site, it was necessary to estimate the risk based on functional safety according to the EN ISO 13849 standard, taking into account the safety functions dependent on the correct operation of the control system. In the advanced safe control system for the hydraulic drive of the tracked undercarriage, the brake valve and the proportional distributor perform tasks related to safety functions; therefore, they are taken into account when assessing the PL. SISTEMA software tools were used to determine the value of safety func-

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tions. Based on the risk graph based on the severity of the injury, the frequency of exposure to hazards, and the possibility of avoiding hazards for the hydraulic drive control system of the tracked undercarriage, the value of the required performance level $\mathrm{PLr} = \mathrm{d}$ was determined. For a Category 3, two-channel control architecture, with a high $MTTFd = 88.1$ years, low $DCavg = 73\%$, fulfilled $CCF = 65$ points, and $PFHd = 9.35\ 10^{-8}$ per hour, the value of the performance level $\mathrm{PL} = \mathrm{e}$ was determined. The condition of a safe advanced control system for the hydraulic drive of the tracked undercarriage has been fully met because $\mathrm{PL} = \mathrm{e} \geq \mathrm{PLr} = \mathrm{d}$. A safe advanced control system for the hydraulic drive of the tracked undercarriage will be implemented in the target industrial version of RBS. The safety functions of the hydraulic drive control system of the tracked undercarriage are checked and monitored using a safety microcontroller ($\mathrm{S\mu C}$). The hydraulic drive control system for the tracked undercarriage was designed and constructed so as to prevent hazardous situations from occurring.

The advanced safe control system was designed and constructed in such a way that:
- a fault in the hardware or software of the control system does not lead to hazardous situations;
- errors in the control system logic do not lead to hazardous situations;
- the drive parameters do not change in an uncontrolled way, where such a change may lead to hazardous situations;
- the control drive system does not start unexpectedly;
- cannot be prevented from stopping the drive if the stop command has already been given;
- an automatic or manual stop remains unimpeded;
- the failsafe devices remain fully effective in stopping the drive;
- safety-related parts of the control system are applied coherently to the entire RBS assembly.

6. Acknowledgement

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