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Technical Paper

Plataforma robótica para operações rigless em poços P&A.

Robotic platform for rigless intervention in P&A wells

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Resumo

A avaliação de integridade de poços fornece importantes informações para o planejamento de abandono de poços, minimizando os custos de intervenções com sonda. Informações mais acuradas sobre o status da integridade mecânica da coluna de produção, do revestimento e da cimentação podem reduzir o grau de incerteza no planejamento da operação de abandono de poço, o que resulta em economia de tempo e recursos em uma operação tão sensível à custos como o abandono. Entretanto, os custos operacionais e a logística exigida para a aquisição desses dados via intervenção de poços convencional acabam por inviabilizar sua realização. Na prática, o abandono de poços (ou as intervenções de uma maneira geral) acabam sendo planejadas de acordo com os dados de projeto, referências de intervenções que tenham sido realizadas ao longo da vida e algumas inferências baseadas na experiência do projetista de intervenção ou abandono.A realização dessas operações por meio de robô autônomo poderá eliminar os custos das unidades de perfilagem a cabo ou flexitubo, guindastes e equipes de operação, além de possibilitar a execução dos trabalhos sem a necessidade de sonda.Este trabalho apresentará o desenvolvimento de uma plataforma robótica modular para realização de tarefas through tubing sem a utilização de wireline, coil tubing ou slickline para realização das intervenções. Serão descritas as etapas já realizadas do desenvolvimento do protótipo, a fase atual e o planejamento para as etapas futuras, as adversidades encontradas até o momento e suas soluções. Finalizando com os resultados de simulações, testes realizados e aplicações futuras.

Palavras-chave: Rigless. Through tubing. Intervenção. Logging. P&A

Abstract

The well´s integrity assessment provides important information for planning well´s abandonment, minimizing the costs of rig interventions. More accurate information about the status of the mechanical integrity of the production column, cladding and, cementation can reduce the uncertainty of planning the well´s abandonment operation, which results in time and resources savings in an operation that is sensitive to costs as P&A. However, the operational costs and the logistics required for the data acquisition by conventional well´s intervention end up making its realization unfeasible. In practice, wells´ abandonment (or interventions in general) ends up being planned according to the project data, interventions references that had been carrying out throughout well´s life and some inferences based on the intervention or abandonment designer experience.Performing these operations by an autonomous robot can eliminate the costs of cable profiling or flexitube units, cranes and, operation teams, in addition to enabling the execution of works without the rig need.This paper presents the development of a modular robotic platform to perform through tubing tasks without using wireline, coil tubing or slickline and, also the project´s phases, results of simulations, performed tests and, applications.

Keywords: Rigless. Through tubing. Workover. Logging. P&A

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1. Introdução

Mechanical integrity evaluation of wells, whether in flux or not, provides information of the utmost importance for planning well abandonment, temporary or permanent, to minimize the high costs of drilling interventions for this purpose. More accurate information about the status of the mechanical integrity of the production column, coating and cementation can reduce the degree of uncertainty in planning the well abandonment operation, which would certainly result in time and resources savings in an operation so sensitive to costs such as abandonment. However, the operational costs and the logistics required to acquire these data via conventional well intervention end up making it impossible to do so. Depending on the conditions of the well, plugging and abandonment (P&A) operations can present high costs even more in the case of offshore wells (Oil & Gas UK, 2015). In order to reduce this cost, Riserless Light Well Intervention (RLWI) operations and new techniques have been studied and applied (Prensky, 2010; Moeinikia, 2014; Varne, 2017)

In practice, the abandonment of wells (or interventions in general) ends up being planned according to the project data, with references about interventions that, perhaps, have been carried out throughout their life, as well as some inferences based mainly on the designer's experience of intervention or abandonment.

The performance of these operations by means of an autonomous robot may reduce the costs of cable or flexitube profiling units, cranes and operation teams, in addition to allowing the execution of works without the need for a rig. Profiling services or specific pressure, flow and temperature records, for example, may be performed prior to the installation of the rig in the well to carry out abandonment operations. Likewise, any other measurement that influences the determination of residual integrity can be incorporated into the robot, allowing the operator to collect data at any time, according to the operational need, by means of remote activation.

The modularity concept of the robot adds to the equipment the possibility of developing new profiling and well monitoring tools, making it possible to also adapt existing equipment for coupling to the equipment.

2. Development description

The platform development is based on four phases. The first phase is the conceptual development, which includes bibliographic research and research of existing tools, in addition to technical definitions. Then the equipment and component development begins, through 3D CAD drawings and simulations. Currently, the construction of the prototype is being carried out to later start the final assembly stage and functional tests.

The robotic platform will allow the application of several logging and inspection through-tubing tools. Initially, it will have pressure and temperature sensors, joint and ending locators, and internal diameter measurement as resident tools for evaluation and assistance in positioning the platform inside the well. As the platform is autonomous, the decision making process of the robot is simulated by carrying out several tests using proper estimators, such as Kalman and histogram filters, in scenarios based on the signature of real wells. Its control system is being developed in such a way that the equipment has the ability to make autonomous decisions in real time. The modules for locomotion, sensors, power, rescue and electronics are being developed to optimize the robot internal space and allow the insertion of new logging and intervention tools.

In addition to the stand-alone platform, a launch and communication mast is being designed. The mast acts as a docking station for positioning the robot before the beginning and after the end of the operation. In terms of safety, the mast will include isolation valves and pressure relief mechanisms, to act as a safety barrier, allowing the robot to enter and exit the well without causing operational disturbances and/or damage to the environment. This equipment also connects the robot to the control system that is external to the well. Through a human machine interface, it is possible to collect the operation data for further analysis, to recharge the system, and to evaluate the platform's functionality without the need to remove it from the well.

3. Development description

To delimit the scope of development, some premises are adopted in this development. The robotic platform must work according to the characteristics of a well-defined model, where it must be able to work through-tubing in vertical and horizontal wells, considering possible incrustations that would cause changes in the internal diameter of the production column, as well as being able to deal with concentrations of H_2S and CO_2. The robot nominal diameter 4-1/2” is chosen as a reference for a first prototype, meeting all API weights for this column diameter. In this way, the same equipment must function within internal diameters between 3,255 "and 4,052". However, the robot must also be scalable to other column diameters.

An application scenario is defined, where the maximum temperature value is 120°C and the maximum pressure is 5.5ksi. The equipment must be able to operate with and without a flow contrary to its movement and, for the calculation of the autonomy estimate, the maximum column depth is fixed at 3.5 km. Also, for a first version, the robot must be able to perform some measurements such as temperature, pressure, internal diameter of the production column and also locate the casing collars.

The robotic platform must be able to identify its location in the column, as well as to identify restrictions that prevent its locomotion. Upon reaching the end of the production column or some passage restriction, it must be able to return to the surface autonomously. It must have a battery system capable of withstanding the determined temperature and pressure conditions. In case of failure during an operation, it must have equipment capable of making conventional fishing viable.

The concept of a modular platform should also be adopted, providing for the possibility of inserting new commercial modules or additional especially developed equipment.

4. Development

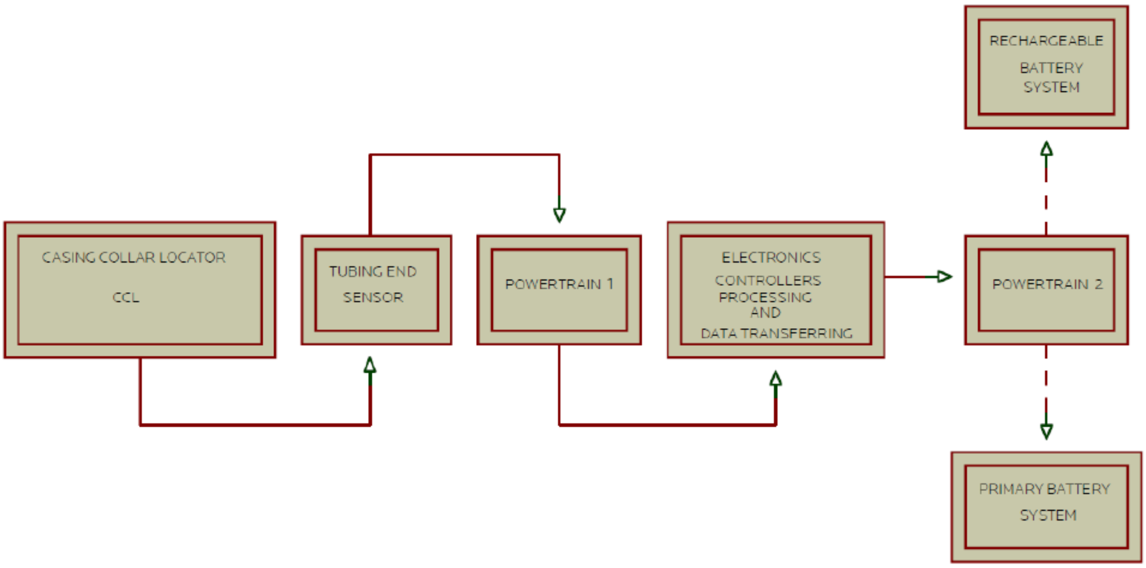
After the previous study on through-tubing logging equipment and systems (Heddleston,2009; Prensky,2010, Abdelmonem,2019), it is possible to focus on the design of a basic structure for the robotic platform. Based on other types of through-tubing equipment, and to minimize the load effect of the fluid passing through the robotic platform, a free space between the robot's outer diameter and the minimum internal diameter of the 4-1/2” columns is estimated as at least 1/8 ”, as shown in Equation 1:

$$\emptyset_{ext_{rob}} = \emptyset_{int_{tub}} - 2 \,.\, {}^{1}/_{8}{}'' = 3.255'' - 0.25'' = 3.005'' \qquad (1)$$

Thus, the maximum external diameter defined for the robotic platform is 3”.

The definition of the modules of the robotic platform is the next step, where Figure 1 presents the block diagram with the modules.

Figure 1 – Block diagram of the modules in the robotic platform



Source: Authors

The module called CCL includes pressure, temperature and joint location sensors; the TUBING END SENSOR is the module responsible for measuring the internal diameter of the pipe and detecting the end of the column; POWERTRAIN 1 and 2 are locomotion modules, including motors and a production column diameter adjustment system; ELECTRONICS is the module with control electronics, power and autonomous decision making; and BATTERIES is the module for powering the platform.

Then, a critical analysis of failures and effects is performed. The main objective of this analysis is to identify the relevant failure modes and the underlying failure mechanisms for each subsystem, and to assess the associated risks. For this analysis, specialists in electronics, robotics, control, mechanics, downhole tools and software have been consulted. And, for each subsystem, failure modes, their causes and effects, probability of occurrence, severity and detection mechanisms are defined. After the manufacture of the parts is finished, a new round of analysis will be carried out and the information from this analysis will be updated.

The first approach is focused on a model for performing CFD simulation. The initial concerns are based on dimensions and geometries that can affect this type of analysis. Figure 2 illustrates the first model and modules.

Figura 2 – Robotic platform

Source: Authors

In order to reduce the weight of the equipment, as well as better dimensioning the motors, simulations are carried out in search of a minimum wall thickness that could withstand the pre-established pressures and temperatures without collapsing. Assuming a relationship between the outer diameter of the robotic platform and the wall thickness greater than 10, a wall thickness between 2 mm and 3.5 mm is estimated. Initially, two materials were chosen for simulations, Ti-6Al-4V titanium (2.5mm thick) and 17-4PH H900 stainless steel (2.0mm thick). These materials have high yield strength S_y, as shown in Table 1, allowing smaller wall thicknesses and good general resistance to corrosion. However, titanium has the advantage of its lower density, which is slightly more than half the density of stainless steel.

Table 1 – Material properties

Material	E (GPa)	Poisson's ratio	S_y (MPa)	S_u (MPa)	□ (g/cm^3)

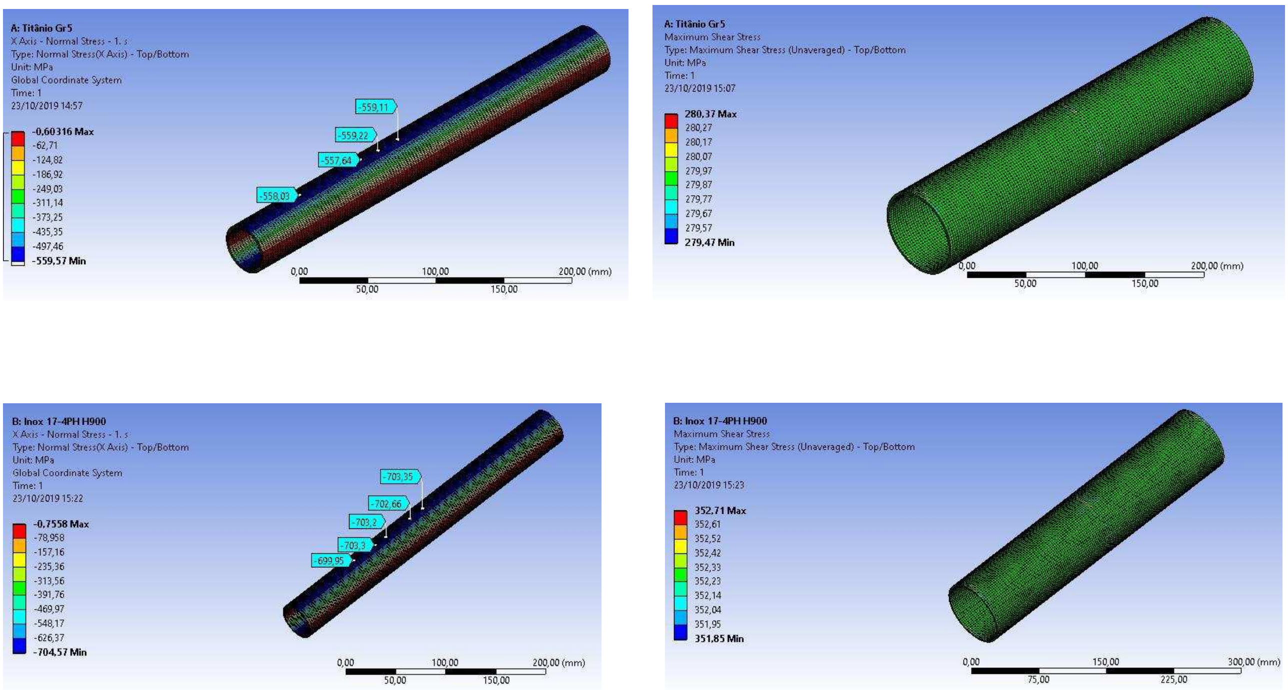
Grade 5 Titanium Ti-6Al-4V[i]	110	0.32	1110	1190	4.4
SS 17-4 PH H900[ii]	190	0.28	1250	1390	7.8

Source: i - https://www.makeitfrom.com/material-properties/Solution-Treated-and-Aged-Grade-5-Titanium

ii - https://www.makeitfrom.com/material-properties/H900-Hardened-S17400-Stainless-Steel

The encapsulation and the cylindrical structure can be treated as a thin-walled cylindrical body (Groehs, 2002), for stress evaluation. This way, von Mises, compression and shear stresses are simulated. Figure 3 illustrates some results while Table 2 presents the critical output data found for each combination of material and wall thickness.

Figure 3 – CFD simulations for thin-walled cylindrical specimens



Source: Authors

Table 2 – Simulation results for each material and wall thickness

Material	Von Mises (MPa)	Compression (MPa)	Shear (MPa)	Safety factor

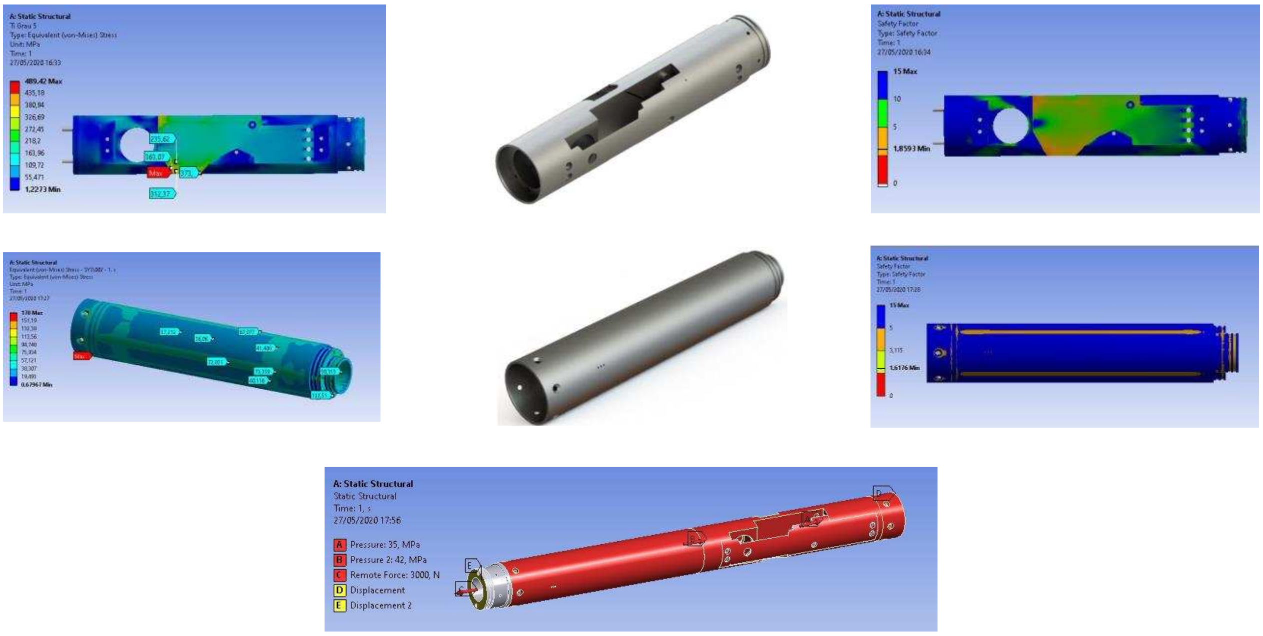
Grade 5 Ti-6Al-4V (2.5mm)	496	559	280	2.24
SS 17-4 PH H900 (2.0mm)	630.3	703	353	1.99

Source: Authors

After this analysis, Grade 5 titanium is defined as the base material for the structures of the robotic platform.

The powertrain module is also simulated to check the integrity in an operating situation. Due to the fact that the parts are not symmetrical, preliminary simulations are performed separately on parts to identify the magnitude of the involved stresses and strains, for a later simulation of the assembled locomotion system. Figure 4 shows an illustration of the simulated system.

Figure 4 – Simulations on the locomotion system



Source: Authors

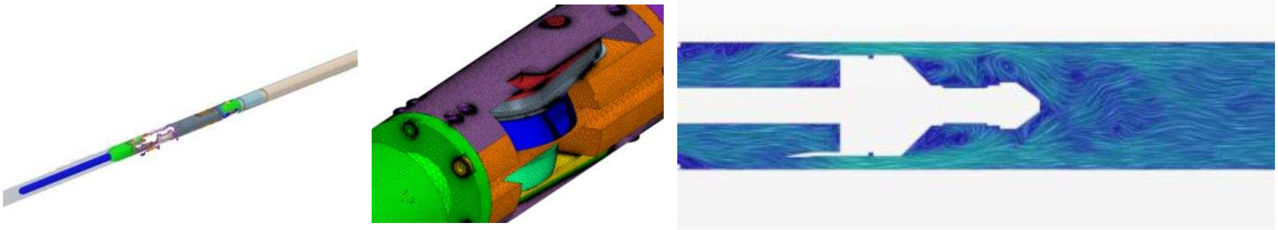
With the results of these simulations, it is possible to validate the use of Grade 5 titanium as a structural material for the powertrain module.

In addition to the material simulations, CFD analyses are performed (Figure 5) to verify the impact of drag forces on the robot, as well as the level of disturbance during the operation of the equipment. The concept of the analysis is to simulate a real well condition, with the robot in the descent and ascent conditions. To reduce computational costs, some simplifications are adopted: the robot remains in a stationary condition, a relative speed is applied to the flow (0.167m/s), the column internal diameter is 3.8 ”, the fluid is considered incompressible and laminar with 85% BSW and equivalent viscosity of 1cP at 120°C. The uniformity index γ, see Eq.(2), is calculated in order to estimate the distance at which the flow returns to a state similar to the undisturbed state.

$$\gamma = 1.0 - \int_{A_0} \frac{\varphi dA}{(2U_{avg}A_0)} \quad , \quad \varphi = \left| |U| - U_{avg} \right|, U_{avg} = \int_{A_0} \frac{UdA}{A_0} \qquad (2)$$

Here, the flow will be considered undisturbed when the uniformity index is within 1% of the index upstream of the robot and stabilized (standard deviation < 0.3%). The results are shown in Table 3.

Figure 5 – CFD analysis



Source: Authors

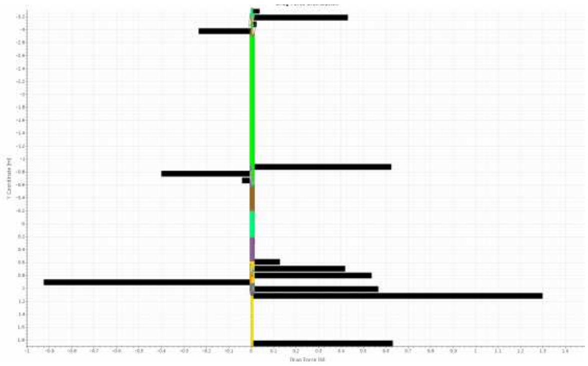
Table 3 – CFD results

Condition	Flow (bpd)	Robot direction	Robot relative speed (m/s)	Flow relative speed (m/s)	Drag (N)	Pressure drop (bar)
1	0	+y (descent)	+0.167	-0.167	3.4	0.006
2	0	-y (ascent)	-0.167	+0.167	38.9	0.006
3	2000	+y	+0.167	-0.252	78.4	0.053
4	2000	-y	-0.167	+0.081	12.0	0.016
5	6000	+y	+0.167	-0.422	192.2	0.280
6	6000	-y	-0.167	-0.089	13.8	0.180
7	10000	+y	+0.167	-3.582	9970.0	0.642
8	10000	-y	-0.167	-3.248	8368.2	0.510

Source: Author

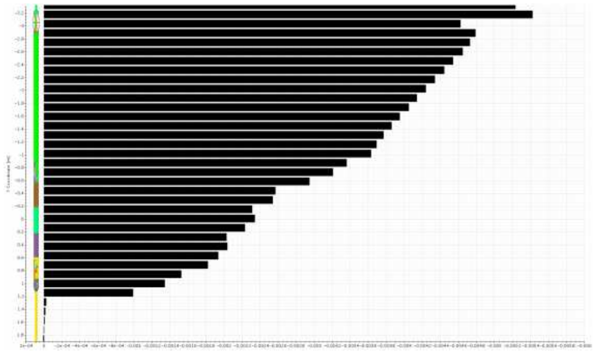
To illustrate the simulation, data from condition 1, robot descending into a well with no flow, is shown in Figs. 6-8. Figure 6 shows the distribution of the drag force along the length of the robot. It is observed that the region with a high number of external parts, variation of the external diameter, and parts with edges, has a greater distribution of loads. The resulting drag force for this flow condition is 3.4 N. As shown in Figure 7, due to a significant variation in the external diameter of the equipment, the region indicated in yellow and green has a higher pressure loss rate than the region in blue. The uniformity index of the robot is 93.5% and stabilizes 4 meters after the beginning of the disturbance (the point at which the flow begins to pass through the robot's body). The length of the disturbed flow downstream of the robot is 1.3m, see Figure 8.

Figure 6 – Hydrodynamic drag distribution along the robot longitudinal direction



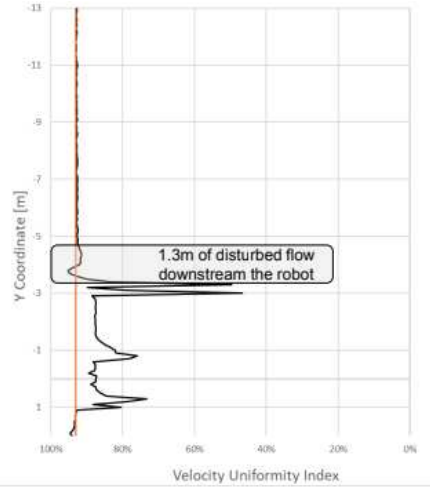
Source: Author

Figure 7 – Accumulated pressure drop



Source: Author

Figure 8 – Uniform velocity index



Source: Author

DC motors have been chosen as an option for locomotion of the equipment. In these types of motors, the larger their diameter and length, the greater the applied torque, specified according to the application for an optimal efficiency. Naturally, the smaller the robot wall thickness, the larger the diameter of the chosen motor may be. The simulation results and the choice of Grade 5 titanium as the structural material allow the selection of motors with a good torque ratio that meet the development needs.

With the main components defined and the powertrain module properly designed, it is possible to calculate the energy consumption of the robot. Assuming the premises presented in Table 4, one can calculate the current consumption and the minimum total capacity for the operation.

Table 4 – Assumptions for the battery assessment

Description	Symbol	Value	Unit
Robot mass	w_r	45	kg
Sensors mass	w_s	5	kg
Payload	w_p	20	kg
Rolling resistance	ρ	35	N
Wheel diameter	D	70	mm
Gear ratio	r	19	-
Gearbox efficiency	ϵ_g	0.85	-
Transmission	Tr	6.33	-
Transmission efficiency	ϵ_t	0.9	-

Velocity constant	k_v	40.5	RPM/V
Nominal voltage	V	48	V
Torque gradient	d_v	2.905	RPM/mNm
Seal loss	S_l	7	W
Torque constant	k_t	68.05	mNm/A
Safety factor	-	1.5	-

Source: Authors

To calculate the energy consumption of the robot while climbing to the surface, the worst case is used in relation to flow, condition 2 of Table 3. The maximum continuous torque in the last reduction stage (τ_w) is obtained through:

$$\tau_w = [(w_r + w_s + w_p) \cdot g + y_{up}(0) + 4\rho] \cdot \frac{D}{2} = (70 \cdot 9.8 + 3.1 + 140) \cdot 0.035 = 29 \text{ Nm} \quad (3)$$

while the torque required by the motor (τ_E) in relation to external forces is

$$\tau_E = \frac{\tau_w}{(r \cdot tr) \cdot (\epsilon_g \cdot \epsilon_t)} = \frac{29}{120.27 \cdot 0.77} \approx 310mNm \quad (4)$$

After calculating the relative speed on the wheels, see Eq.(5), it is possible to arrive at the additional torque caused by the sealing friction, shown in Eq.(6).

$$v_w = [k_v \cdot V - (d_v \cdot \frac{\tau_w}{2})] \cdot (r \cdot tr)^{-1} = (140.5 \cdot 48 - 2.905 \cdot 290 \cdot 0.5) \cdot (120.27)^{-1} \approx 53 \text{ RPM} \quad (5)$$

$$\tau_s = 4 \cdot \frac{S_l}{v_w} = 4 \cdot \frac{7}{53} \cdot \frac{60}{2\pi} = 5 \text{ Nm} \quad (6)$$

Therefore, the total maximum torque from the motor becomes

$$\tau_m = \tau_E + \frac{\tau_s}{(r \cdot tr) \cdot (\epsilon_g \cdot \epsilon_t)} = 310 + \frac{5000}{120.27 \cdot 0.77} = 364 \text{ mNm} \quad (7)$$

Through the torque constant, the maximum current consumption is reached through

$$I = \frac{\tau_m}{k_t} = \frac{364}{68.05} = 5.35 \text{ A} \quad (8)$$

With these premises, a rise time in the order of 5h is estimated, see Eq.(9), and an energy capacity of 26.75Ah for the robot to rise to the surface, see Eq.(10).

$$\mathrm{T_a} = \frac{3500}{\mathrm{v_w} \cdot 2\pi \cdot \frac{\mathrm{D}}{2}} \cdot \frac{1}{60} = 5 \text{ h} \qquad (9)$$

$$\mathrm{C_{(subida)}} = I \cdot T_a = 26.75 \text{ Ah} \qquad (10)$$

For the case of descent from the robotic platform to the end of the well, it is assumed that the weight of the robot is greater than the maximum drag force, which leads to the absence of external forces that demand energy from the motor. However, the efficiency of the transmission in the reverse direction is almost zero, leaving the motor responsible for breaking the internal frictional forces. Therefore, repeating the same analytical logic of Eqs.(3-10), it is possible to reach the necessary energy capacity for the descent, which is 3.6Ah and a total capacity of 45.53Ah, see Eq.(17).

$$v_w = [k_v \cdot V - (\mathrm{d_v} \cdot \tfrac{\tau_w}{2})] \cdot (r \cdot tr)^{-1} = (140.5 \cdot 48 - 2.905 \cdot 0 \cdot 0.5) \cdot (120.27)^{-1} \approx 56 \text{ RPM} \qquad (11)$$

$$\tau_s = 4 \cdot \frac{S_l}{v_w} = 4 \cdot \frac{7}{56} \cdot \frac{60}{2\pi} = 4.77 \text{ Nm} \qquad (12)$$

$$\tau_m = \frac{\tau_s}{(r \cdot tr) \cdot (\epsilon_g \cdot \epsilon_t)} = \frac{4770}{120.27 \cdot 0.77} = 52 \text{ mNm} \qquad (13)$$

$$I = \frac{\tau}{k_t} = \frac{52}{68.05} = 0.76 \text{ A} \qquad (14)$$

$$T_d = \frac{3500}{v_w \cdot 2\pi \cdot \frac{D}{2}} \cdot \frac{1}{60} = 4.73 \text{ h} \qquad (15)$$

$$\mathrm{C_{(descent)}} = I \cdot T_a = 3.6 \text{ Ah} \qquad (16)$$

$$\mathrm{C_{(total)}} = (\mathrm{C_{(ascent)}} + \mathrm{C_{(descent)}}) \cdot 1.5 = (26.75 + 3.6) \cdot 1.5 = 45.53 \text{ Ah} \qquad (17)$$

After defining the total capacity required for the equipment, suppliers have been identified for the creation of battery packs, from both primary and secondary cells that meet the project requirements. Note that the battery module will have an induction charging system.

For the insertion and removal of the robotic platform in the well, a launch and receiving mast is under development. This equipment can be coupled in dry completion Christmas trees, onshore or platform wells, and are responsible for delivering the equipment to the well. In a first approach, manual valves will be used, but later they will be replaced by automated valves, allowing automatic opening and closing as the operation progresses. The mast will also be equipped with an induction power transmission system, making it possible to recharge the robotic platform without the need to remove the robot from inside the mast to carry out an eventual recharge of the secondary cells.

5. Considerações finais

In this work, an innovative autonomous robotic platform has been discussed, serving as a tool for through-tubing evaluations. Simulation analyses verify the operability of this system. Although the results found in the CFD analyses are satisfactory, new geometries will be studied to obtain better results in limiting situations, such as within reduced diameters and facing high flow. The mechanical and electronic drawings of the robotic platform have been finalized and are being manufactured for the development of a first prototype version for testing. With the development of the autonomous modular robotic unit prototype, as well as the sensing module and its respective launching mast for applications in dry wells, it will be possible to generate a low cost methodology, adaptable to the operational needs of each well, with high reliability and availability, operating without the need for a rig. This robotic system becomes a new way of assessing the mechanical integrity of oil or gas producing wells and injector wells with dry completion, in order to generate data that can subsidize plugging and abandonment (P&A) operations.

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