S1. WINCH CONSTRUCTION

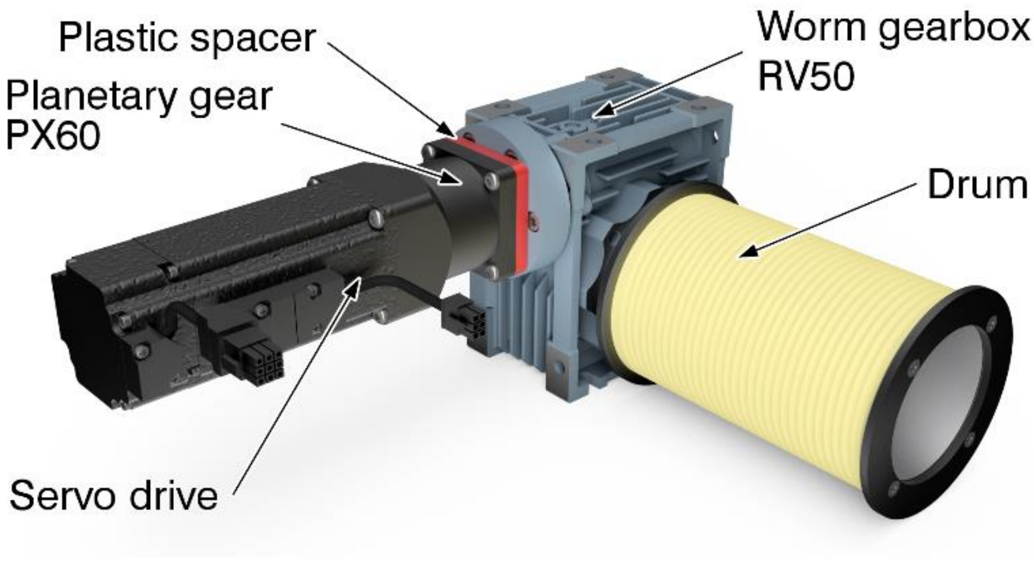

Fig. S1. Winch assembly

The general design of the winch is shown in Fig. S1. The winch is based on an RV50 series worm gearbox with a gear ratio of 1:30. The worm gear of this gearbox is self-braking which means that the input worm shaft cannot be driven by the output gear shaft. Therefore, winch components do not require additional braking systems for protection in case of an emergency. The disadvantage of the worm gear used is its low efficiency at low rotation speed (Fig. S2). However, considering the relatively low ROP of the testing sonde, the efficiency does not greatly affect the power requirements for the winch drive.

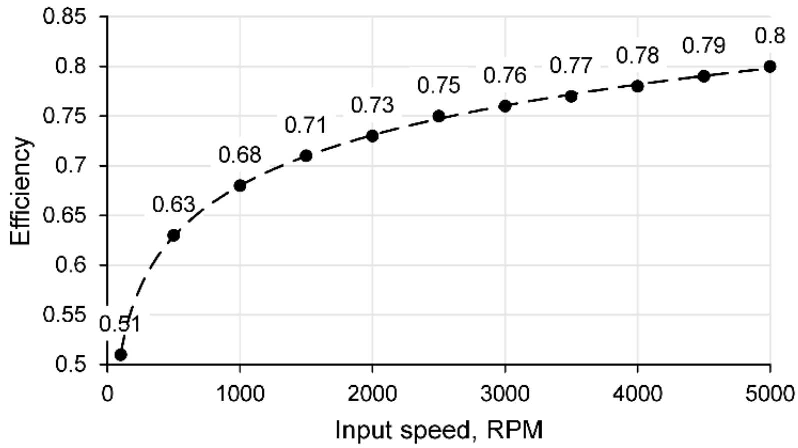

Fig. S2. Dependence of the efficiency of the worm gear on the speed of rotation of the input shaft

For precise control of the winch, a servo drive was chosen. The servo drive has the following characteristics: power – 200 W; nominal torque – 0.64 Nm; maximum torque – 1.92 Nm; nominal speed – 3000 RPM; maximum speed – 5000 RPM. This drive has its own external control unit, which can be controlled both from a computer and from a conventional remote control. The servo drive supports different operating modes. For the test purpose, the constant speed mode was selected. In this mode, the servo drive will try to maintain a constant rotation speed with all available power. Servo drive has a range of rotation speed 1 to 5000 RPM with minimum control step of 1 RPM.

To compensate for the low servo drive power, a small PX60 series planetary gearbox with a gear ratio of 1:6 was installed between the worm gearbox and the servo drive. The efficiency of the planetary gearbox is above 95%, which allows an increase in the torque on the output shaft without significant compromises in the speed of tripping operations. (*Note, that the worm gear type RV50 in the configuration already has the maximum gear ratio*). Therefore, this winch drive configuration has the following nominal and maximum torque values (Fig. S3)

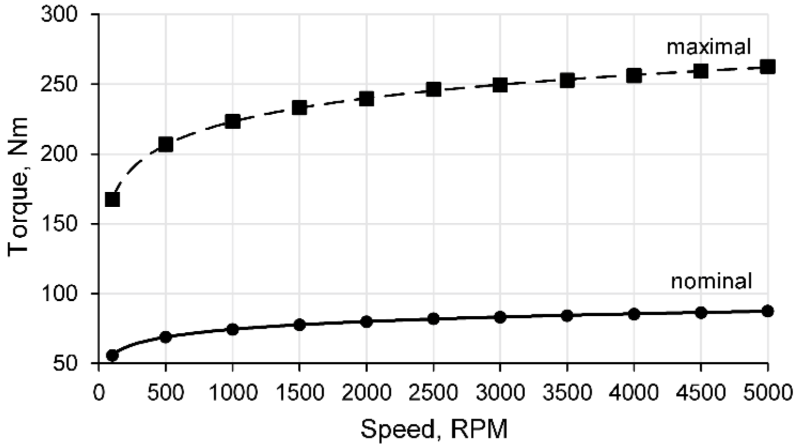

Fig. S3. Dependence of nominal and maximum torque on the winch output shaft vs. servo drive rotation speed

To simplify the design, it was decided to mount a small drum directly on the output shaft of the worm gearbox. The diameter of the drum was chosen so that the axis of the wound cable is a circle with a diameter of 0.107 m. This was done for the convenience of calculations (3 turns are equal to 1 m in length) and easy estimation of the ROP without relying on information from the encoder on the top block. A 5 mm diameter Kevlar rope was selected as the cable. The drum will hold only one layer of the cable. This makes it possible to set a constant ROP on any section of the cable by setting a constant RPM value of the servo drive using an external control unit, without building a feedback loop to the encoder on the top block. For cable laying, a spiral guide is applied to the surface of the drum. Since only one layer of the cable is used, there is no need to employ any cable laying equipment. Because the drum is mounted on the output shaft without additional supports, it is essential to calculate the maximum admissible load. The weight of the test sonde is assumed to be approximately 100 kg and for the calculation, it was decided to take the weight value with a two-fold reserve (Fr_x = 200 daN). This will allow this test stand to be used in the future without modifications for testing of heavier prototypes, as the loadcells in top block can already hold a weight up to 200 daN.

Maximal admissible load [daN] is estimated according to the following equation:

$$Fr_x = \frac{aFr_2}{b + x_{\max}} \tag{S1}$$

where Fr_2 is the max. admissible load in daN, $x_{\max}$ is maximal length of the cable on the drum.

Forces and winch dimensions are shown in Fig. S4. For RV50, Fr_2 = 489.6 daN; a = 0.101; b = 0.076 (Motovario, 2015).

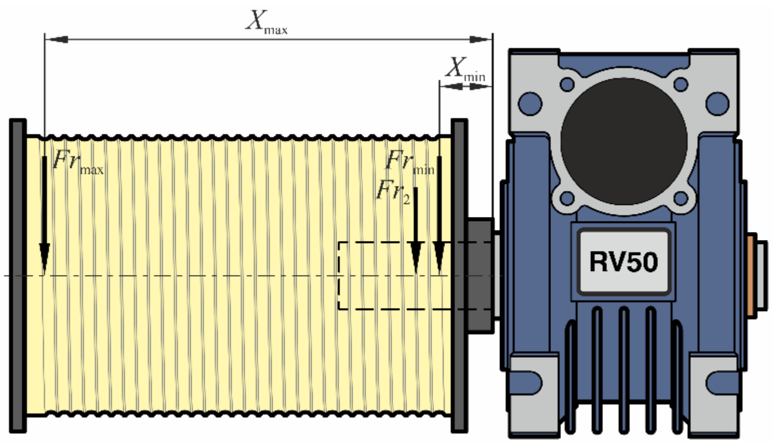

Fig. S4. Forces and drum dimensions

The maximal length [m] of the cable on the drum is equal to:

$$x_{max} = x_{min} + \frac{D_c}{\pi D_d} l_c \quad \text{(S2)}$$

where x_{min} is the length with no cable on the drum (0.02 m), D_c is the diameter of the cable, l_c is the length of the cable, D_d is the diameter of the drum (0.107 m).

Based on all of the above, it is obvious that the limitation of admissible load is the cable length. Let's combine equations S1 and S2, and subsequently determine the cable length value of the l_c.

$$l_c = \frac{\pi D_d}{D_c}\left(\frac{aFr_2}{Fr_x} - b - x_{min}\right) \quad \text{(S3)}$$

Substituting all values into equation S3.

$$l_c = \frac{3.142 \cdot 0.107}{0.005}\left(\frac{0.101 \cdot 489.6}{200} - 0.076 - 0.02\right) = 10.168$$

The closest integer number of turns on the drum corresponding to the resulting cable length is 30 turns.

In cases where test sondes weigh more than 200 daN, the graph in Fig. S5 can be used as reference.

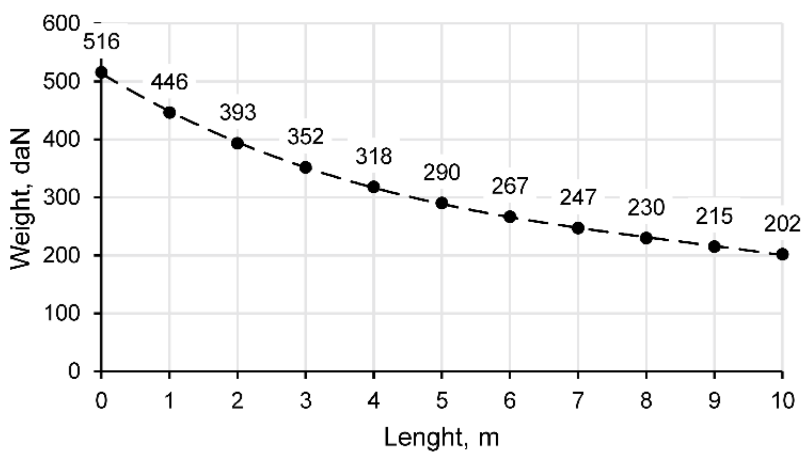

Fig. S5. Dependence of the maximum admissible weight vs. the length of cable on the drum

The ROP [m/h] values on a given winch configuration at different servo RPMs can be calculated from the equation:

$$\upsilon = 60 \cdot \pi D_d n \tag{S4}$$

where n is the angular velocity in RPM.

Maximal rotation speed of servo drive is 5000 RPM. Two gearboxes with a gear ratio of 1:6 and 1:30. Diameter of the drum $D_d = 0.107$ m. So, the maximum possible ROP value that can be obtained on a winch of this configuration is

$$\upsilon_{\max} = 60 \cdot 3.142 \cdot 0.107 \cdot \frac{5000}{6 \cdot 30} = 558.156 \text{ m/h or } 9.303 \text{ m/min}$$

All 10 m of the cable is possible to wind up the winch drum in a minute.

Calculated ROP of different servo drive PRM values is presented in Table S1.

Table S1

Dependence of ROP value vs. servo drive RPM

Servo-drive speed (RPM)	ROP (m/h)	ROP (m/sec)
1	0.112	*>0.001*
2	0.223	*>0.001*
3	0.335	*>0.001*
4	0.447	*>0.001*
5	0.558	*>0.001*
10	1.116	*>0.001*
25	2.791	0.001
50	5.582	0.002
100	11.163	0.003
200	22.326	0.006
500	55.816	0.016
1000	111.631	0.031
2500	279.078	0.078
4000	446.525	0.124
5000	558.156	0.155

Knowing the dependence of ROP value and torque vs. servo drive RPM, the maximum allowable tripping speed for testing sondes of different weights can be calculated according to:

$$\upsilon = \frac{M}{gm} \tag{S5}$$

where M is the torque in Nm, g is the gravitational acceleration in m/sec^2.

Substituting the torque values (Fig. S3) and the ROP values (Table S1) into Eq. S5 gives nominal and maximum rotation speed of the servo drive (Fig. S6).

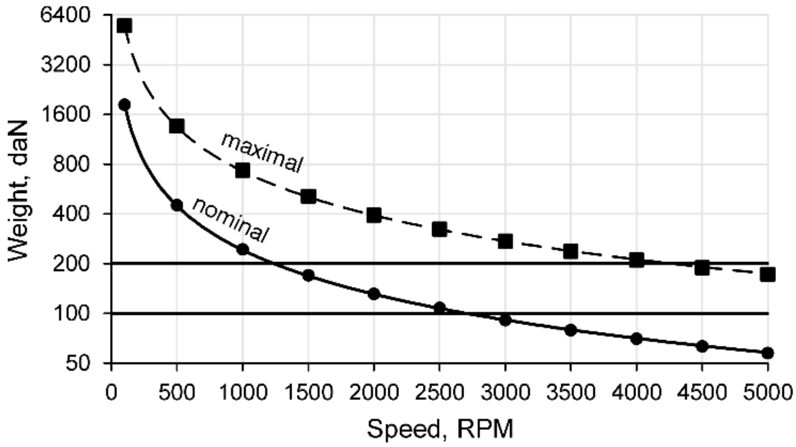

Fig. S6. Dependence of nominal and maximum admissible weights vs. servo drive rotation speed.

For lifting a test sonde weighing 100 daN, the maximum servo drive speed should not be set higher than 2705 RPM. Substituting this value into Eq. S3 yields the linear speed of 5.033 m/min. Therefore, it will take approximately two minutes to lift the testing sonde to the maximum cable length of 10 m. For a maximum design weight of 200 daN, the speed that will not exceed the nominal servo drive parameters is 1238 RPM, and the linear speed in this case is 2.303 m/min.

REFERENCE

Motovario, Worm gear reducers and worm geared motors. 2015 https://www.motovario.com/eng/download/worm-gear-reducers--vsf-series