MECHATRONICS

P01 - Analysis and design of an electric nut runner for tightening of bolted joints

Group Assignment

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1. Introduction

The assignment is done in groups of 3 students. Although you are expected to solve the assignment tasks on your own, there are 3 hours of assistance per week (referred to as *Project* or *Laboration* in the course schedule), where assistants are available for answering specific questions that you have prepared.

The assignment report shall be handed-in via Canvas, due on Tuesday 15th of October, along with the corresponding data files (models, simulation results etc.). Questions can be answered by any of the course assistants, either during the exercises or else preferably by e-mail. In case of short questions potentially solved by short answers, those will be given over e-mail as quickly as possible. More elaborate issues will be collected and responded to in person during the Lab sessions or otherwise on times/places as announced by the course assistants and/or communicated in Canvas.

The goal with the assignment is to develop a skill for how to approach and solve a mechatronics design problem using a model-based approach. Based on a targeted product functionality such a skill involves (in short):

- conception of a system based on structured subsystems,
- selection of components,
- modeling and simulation of the system at various levels of detail,
- designing a control system and
- verification of system behavior.

Note: Please read thoroughly the *whole* assignment before starting your work and remember that mastering the assignment also means that you possess skills valuable when it comes to the final written exam, and most importantly in a future engineering career.

Good luck!

2. Reporting

2.1. Evaluation criteria

There is **ONE** report per group. The report is evaluated based on:

- **Correctness and Coverage of Assignment Tasks**
    - Correctness: Make sure that your solutions, results, and conclusions are correct and well-supported by explanations and justifications for your solutions.
    - Completeness: Address all aspects of each task as specified in the assignment.
- **Structure and Readability**
    - Logical Organization: The report should follow a clear, logical structure that is easy to navigate.
    - Conciseness: Be focused and precise in your descriptions by avoiding unnecessary length and redundancy. Make sure that each paragraph and sentence serves a clear purpose in your argument or explanation.
    - Reasoning and Explanation: Clearly explain the reasoning behind your solutions, results, and conclusions.
- **Language and Clarity**
    - Grammar and Syntax: Ensure that your report is free from grammar and syntax errors. The language should be formal, objective, and aligned with academic standards.
    - Technical Language: Use appropriate technical terms where necessary, ensuring that they are correctly applied and contribute to the clarity of your findings.

As to the specific content of the report, please read carefully and stick very closely to what is requested under the different assignment tasks.

2.2. Fair and ethical use of generative AI tools

- You **may** use generative AI tools to gain a rapid overview over a concept or area.
    - Generative AI tools can be valuable for quickly understanding new or complex topics and you **may** use these tools to summarize or explain key concepts to help you grasp the material more efficiently. However, this should only serve as the basis for deeper understanding using the resources provided during the course.
- You **may** use generative AI tools to refine the language of your writing (e.g. help with grammar correction or translation). However, the findings, structure, and content of your work must be your own.
    - You should **not** use generative AI tools to paraphrase or rewrite large sections of text in your report. Your work must reflect your original thinking and analysis.
- You **must** state which generative AI tools you used, as well as the nature and extent of their usage in your report. This requirement follows the course's ethical guideline stating: "In any assessment, every student shall honestly disclose any help received and sources used".
    - You **must** add an **Acknowledgement** section at the end of your report, where you state the generative AI tool(s) that you used and the extent to which these tools were used in your report.

- You must **not** include autogenerated text in your submissions.
    - All reports will be scanned for use of autogenerated text. If such text is identified and you have not clearly stated which generative AI tools you used and the extent to which these tools were used (see previous bullet), **you will fail the group assignment**.

Note: Be aware that generative AI tools can produce biased or inaccurate information, so it is your responsibility to critically evaluate and verify any AI-generated information before using it in your work. Over-reliance on generative AI tools may hinder your learning and development of critical skills essential for your success in this course and your future career.

3. An electric nutrunner for tightening of bolted joints

3.1. System to be designed

Handheld electric nutrunners are used in the manufacturing industry to aid assembly workers in doing precisely controlled bolt tightening, e.g. in the automotive industry. Such a nutrunner is a good example of a quite advanced mechatronic system for which the characteristics of the device itself as well as of the bolted assembly must be considered and analysed together during the design process. **In this assignment we will base modeling, design (some aspects) and analysis on the cordless device** depicted in **Figure 1** (top).

Figure 1 Two examples of angle nutrunners: (top) Cordless (battery-powered) angle nutrunner Tensor ITB-A61-50-10 [1], (bottom) Wired angle nutrunner Tensor ETV STR61-50-10 [2] connected to the Power Focus 6000 [3] controller box.

The main elements of the cordless (battery-powered) Tensor ITB-A61-50-10 nutrunner [1] (**Figure 1** (top)) are a basic cylinder shaped mechanical structure, a battery, a brushless DC-motor, a two-stage planetary gear, a torque transducer, a 90-degree spiral angle gear, an operator interface, a communication interface(s) (Wi-Fi host or client and Bluetooth), a one-piece angle head for attachment to the bolted joint to be tightened, and finally an ergonomically designed handle as the physical interface to the operator. This tool has an integrated controller allowing standalone operation or integration into a larger connected system (Industry 4.0).

Another option is to use a separate (external) controller where multiple tools can be connected to, such as the Power Focus 6000 [3] (**Figure 1** (bottom)), which can operate independently or be connected to a larger system. Wired nutrunners such as the Tensor ETV STR61-50-10 [2] (also seen in **Figure 1** (bottom)) do not include an integrated controller or battery, so they require direct connection to the Power Focus 6000 for their operation.

The transducerized nutrunners presented in this assignment offer tightening programs controlled by torque (by torque transducer) and/or angle with encoder and gyroscope. Some general specifications for the nutrunners can be found in **Table 1**.

Table 1 Technical specifications for the cordless and wired nutrunner examples

Property	**ITB-A61-50-10 (cordless)**	**ETV STR61-50-10 (wired)**
Torque Max/Min (Nm)	55/10	55/10
Maximum speed (rpm)	587	735
Weight (kg)	2.5 with battery	1.6 without wire
Motor power (W)	1500	1500
Note: The wired tool is powered by the Power Focus 6000 which incorporates many control features.		

3.2. Bolt tightening

Tightening of threaded bolt and nut assemblies requires control of both torque and angular motion to reach the desired preload (i.e. clamping force) of the bolted assembly. Thus, in advanced electrical nutrunners both the turning speed (or angle) and the turning torque are controlled. Therefore, the geometry of the assembly, the material characteristics of the involved components, and the friction between the parts (that move relative to each other during tightening) must first be understood to control the tightening process.

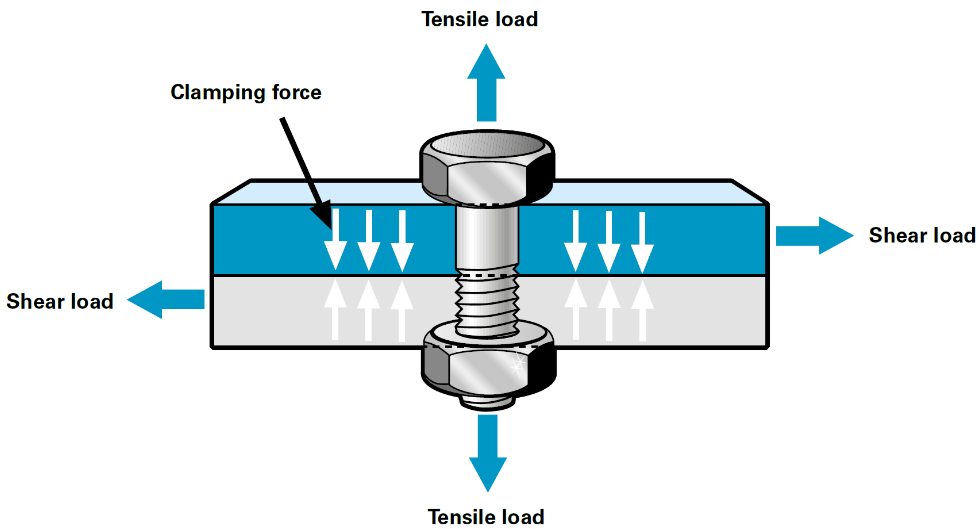


Figure 2 Main components and acted forces during the tightening process [4].

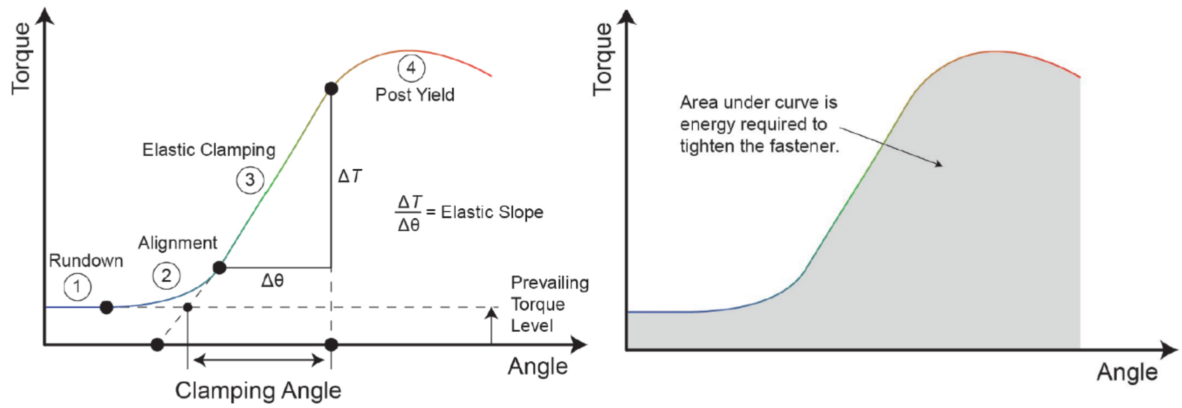
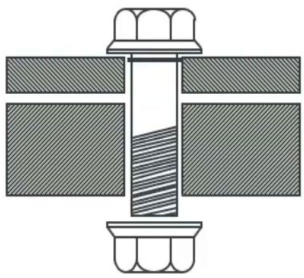


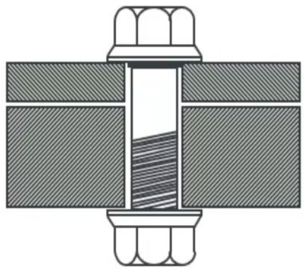
Figure 3 Applied torque with respect to bolt rotation and energy transfer process during bolt tightening.

Tightening a bolt corresponds to an energy transfer process where the area under the torque-angle curve equals the energy consumed during the tightening process (**Figure 3**). The process of tightening a fastener involves four distinct zones (or phases):

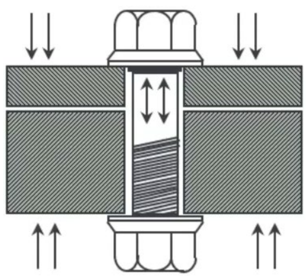
- A *rundown* zone (① in **Figure 3**) in which the nut is turned until the joint members start to align. This phase is typically programmed with a high angular velocity for a specific number of revolutions (threads), while it lasts until a prevailing torque level is achieved.



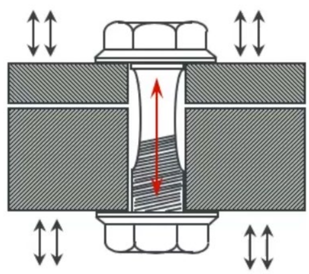
- An *alignment* zone (also called snugging or draw-down) ② in which the mating surfaces of the joint are pressed into alignment to achieve a “snug” or seated state.



- An *elastic clamping* zone ③, which corresponds to elastic deformation (stretching/compression) of the joint members where in principle there is a linear relationship between turning angle and elastic deformation. In this phase the clamping force is built up and generally a lower angular velocity is used compared to the rundown phase to avoid any overshoot (overtightening) and to avoid operator discomfort.



- Finally, the yield point of a joint member is reached, and the following deformation is no longer elastic, but plastic (depicted as the post-yield zone ④).



While the above four are the main zones (or phases) encountered in a tightening process, there are many different tightening techniques recommended by nutrunner manufacturers, which are designed to counter undesired effects (e.g. joint relaxation, friction effects, operator fatigue):

- A fixed displacement reverse program to remove torque on a reaction bar (or the operator) to aid removing the tool's socket from the screw/nut.
- Two-stage or impulse tightening to deal with joint relaxation (i.e. the gradual creeping or settling of joint components) or embedment (i.e. when the head of a bolt or nut buries into a joint component)
- Advanced tightening techniques involving multiple steps, speed ramp-down before shut-off etc.

3.3. The system in some more detail

The overall system to be analysed and partly designed has the components, configurations, characteristics and parameter data as described in this section.

3.3.1. The nutrunner

A **cordless** angle nutrunner - transducerized type ITB-A61-50-10 [1] by Atlas Copco Tools is under study. The tool has dimensions according to **Figure 4** below. **In this assignment, the tool is oriented horizontally, whereas the bolt is oriented vertically**.

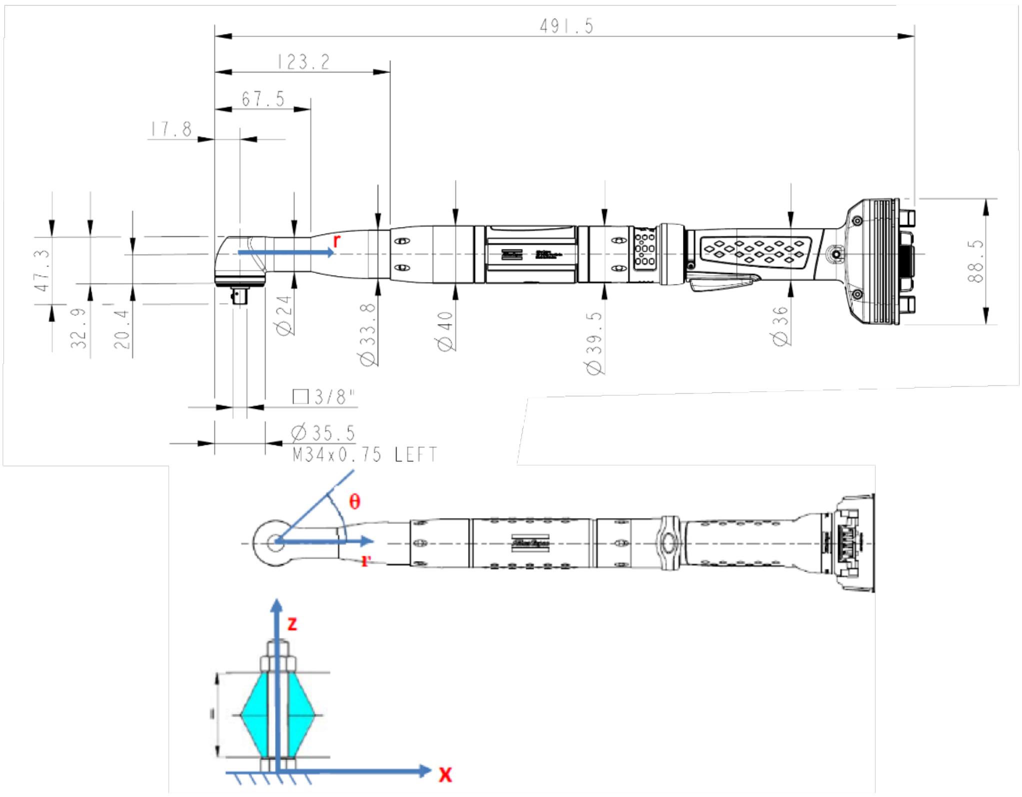


Figure 4 Indicative dimensions of the cordless nutrunner with assigned coordinate systems.

In addition to the coordinates of **Figure 4**, the ***φ-coordinate*** corresponds to rotation (of motor and transmission parts) around the tool-fixed r-axis, the ***θ-coordinate*** corresponds to tool rotation around the z-axis of the inertial reference frame x-y-z, while the ***α-coordinate*** corresponds to nut rotation around the same z-axis.

Some nutrunner data needed for the assignment can be found in the nutrunner datasheet [1] (also available in the Canvas assignment page). Note, however, that for this assignment we will use different motors than in the real case and these motors will be operated at 24 V. There is a selection of different motor models with slightly different characteristics, **one** of which is assigned to your group (check the Canvas assignment page to see which motor has been assigned to you). **Only use data for the (single) motor model which is assigned to your group.** All motors are manufactured by Faulhaber and the specifications for each model can be found by looking up the model's name in [5] or by clicking the links added in **Table 2**. Many of these motors are available for different voltage ratings, in this assignment we will use the **24V** variants. Some relevant specifications to these motors can be found in **Table 2**, however, you are advised to check their latest datasheets for any updates to these values.

Note: These motors will be modelled as DC-motor equivalents, although they are of different type (brushless). This is done for simplification purposes and Faulhaber already provides the equivalent DC-currents in their datasheets (see the application note by Faulhaber [6], which is also available in the Canvas assignment page).

Table 2 Motor specifications

No.	Motor Model	Nominal torque (mNm)	Terminal resistance phase-phase (Ohm)	Friction torque, dynamic (mNm/min^{-1})	Back-EMF constant (mV/min^{-1})	Torque constant (mNm/A)	Terminal inductance phase-phase (µH)	Rotor inertia (gcm^2)
1	3268 024 BX4	96	1,47	$1{,}1 \cdot 10^{-3}$	4,534	43,5	110	63
2	3564 024 B	66	1,1	$1{,}8 \cdot 10^{-4}$	2,08	19,9	190	34,9
3	3274 024 BP4	158	0,253	$9{,}24 \cdot 10^{-4}$	2,94	28,1	64,2	48
4	2264 024 BP4	59	0,22	$1{,}15 \cdot 10^{-4}$	1,236	11,8	24	9,2
5	4490 024 B	190	0,22	$7{,}72 \cdot 10^{-4}$	2,53	24,2	73	130

The **following assumptions and parameter values apply**:

- On the output shaft of the tool, a socket is attached to fit the nut to be turned. We assume this socket is stiffly connected and has a tight fit on the nut. In this way we can consider the tool chassis rotation θ to be in the horizontal plane only.
- The mass centres of the battery and of the tool itself (excluding the battery) are assumed to lie on the r-axis. The mass centre of the battery lies on the r-coordinate at 500 mm. The mass centre of the tool itself (excluding the battery) lies on the r-coordinate at 250 mm.
- The electromechanical actuation system of the tool is depicted in **Figure 5** below.
- The transmission ratio of the 90-degree angle gear is equal to 1.
- The tightening process only include the rundown and elastic phase.

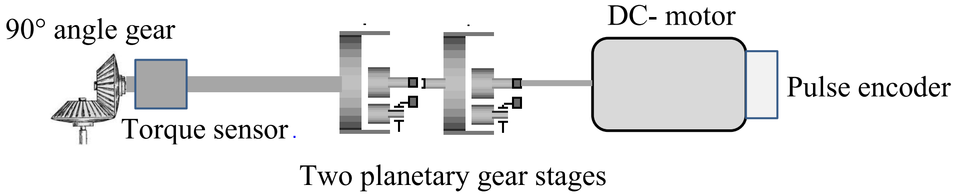


Figure 5 The electromechanical actuation system of the nutrunner.

3.3.2. The bolted assembly

When tightening a bolted joint, the torque is transferred from the tool (and operator) to the nut. The real tightening process is quite complex considering the non-linear friction conditions, the stretching and twisting of the bolt, as well as compression of the assembly members being fitted together. In this assignment, we will consider the nut running process as consisting of two phases: rundown and clamping (**Figure 3**). For the whole assignment, the **bolt head is considered fixed to a reference frame**.

- Run-down phase:

In the run-down phase, the tool is to overcome only the friction and the inertia of the free-running nut. The reaction torque on the tool is hence very limited and therefore we **assume that the tool remains in a fixed orientation** although it will follow the nut downwards (no reaction forces on the operator although he/she is assumed to counteract gravitational forces of the tool). Additionally, we assume that the **friction conditions are linear.**

- Clamping phase:

In the clamping phase the screw-nut assembly is **modelled as a stiffness** (comparatively stiff, with damping). You can regard this stiffness as a spring/damper acting along the centre axis of the bolt, while the very stiff "spring behaviour" corresponds to the stretching of the bolt during tightening. **We disregard the compression elasticity of the assembly members being pressed together and we also disregard potential twisting of the bolt**.

Initially when setting up the model equations we assume that the conditions are linear, but since the bolted joint is self-locking (i.e. rotation of the nut leads to longitudinal stretching of the bolt, but stretching of the bolt does not – due to friction – lead to nut rotation) the final behaviour is non-linear.

4. A first set of assignment tasks

The assignment tasks correspond to typically important engineering tasks that are performed during design of a mechatronic system, although in this case a conceptual design is already present.

The assignment is structured in an incremental way, going step-by-step from rather simple tasks to more complex issues.

- When solving the tasks, it is important to adopt a structured approach simplifying reuse of early results in later stages of the process, and to document the work throughout (this will substantially facilitate creating a report of high quality).
- When drawing block diagrams, you should adopt a principal ordering of signal lines and blocks similar to what is used in the course lectures.
- Simulation and analysis are to be done using MATLAB and Simulink. Analysis and demonstration of system behaviour will use MATLAB/Simulink plots. **Make sure to scale plots with respect to time and amplitude so that the interesting behaviour is clear. Make sure also that the scaling of axes is done with clearly readable font sizes.**
- In the report and for each model you derive during the assignment, all newly introduced (i.e. not given earlier) model parameter values must be numerically stated.
- **Make sure that you are using the correct datasheet for the motor assigned to your group.**

The first set of assignment tasks deals with modeling, analysis and the first stage of control design of the above system for the purpose of angular velocity control during the run-down phase (**Figure 3**). The main subsystems having potentially large impact on the system behaviour are the **DC-motor, the gearings and shafts, and the nut/bolt system.** These main subsystems are modelled, and their behaviour analysed such that the models can be verified to be reasonable and of suitable complexity (not unnecessarily detailed) for control design.

5. Assumptions

- Lumped parameters and linear models can be used. In this case, linear models mean linear differential equations with constant coefficients.
- All mechanical interconnections except the planetary gear stages are considered as infinitely stiff.
- The damping in the overall system comes from DC-motor resistance, the linear friction in the nut, and finally the friction in the tool (also considered linear).
- There are **no losses** in the gearbox (in reality, there would be 3 – 5 % energy loss per gear stage).
- The nutrunner will not run continuously, this allows for a design utilizing the motor's stall torque.
- The angle gear, output and input shafts can be considered rigid (i.e. no flexibility)
- All components of the transmission are assumed to be made of steel.
- The flexibility in the transmission is assumed concentrated to the two planetary gear stages and equals in total k_t = 739 Nm/rad as **estimated on the output (load) side of the planetary gear pair**.
- The transmission damping (friction) is assumed linear and equals to d_t = 1.5 Nm·s/rad as **estimated on the output (load) side of the planetary gear pair**. The damping in the transmission should be considered as relative (see Janschek p. 246). This assumption agrees with the simplified transmission model shown in **Figure 8**.
- The damping in the screw/nut assembly (joint friction) is assumed linear and equals d_j = 1.5 Nm·s/rad. The damping in the nut/screw should be considered absolute ("sky hook" type – see Janschek p. 245-246). This assumption agrees with the simplified transmission model shown in **Figure 8**.
- The stiffness k_j (longitudinal) of the steel screw is calculated from screw dimensions and material properties. **The screw is assumed not to undergo any torsional twist.**

6. Additional information

The main subsystems of the nutrunner are depicted in **Figure 6**, while **Figure 7** presents the main parts of the transmission including some of the dimensions.

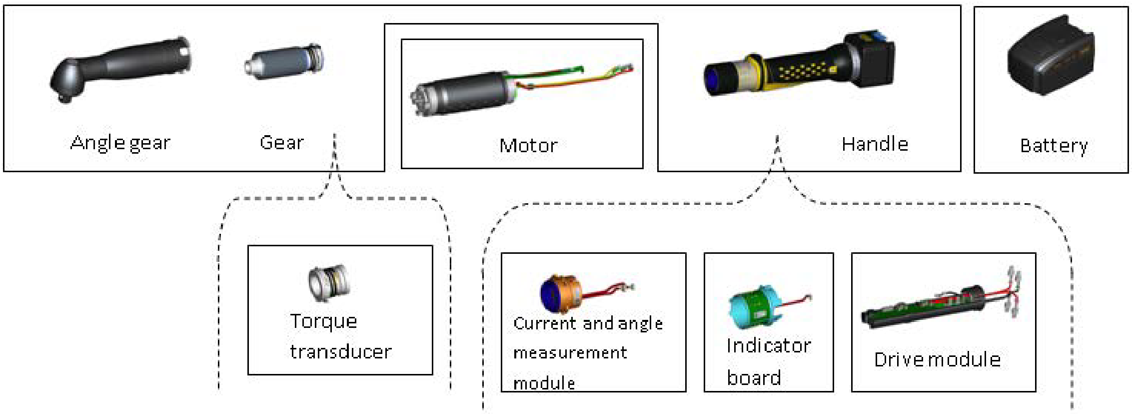


Figure 6 The main subsystems of the cordless nutrunner.

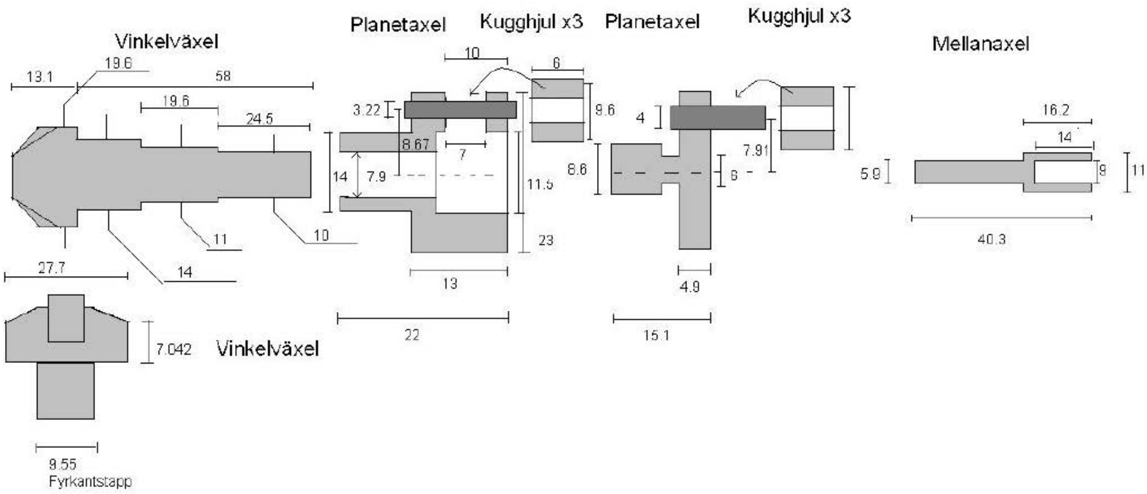


Figure 7 Nutrunner transmission parts including indicative dimensions.

With these assumptions, the transmission model can be simplified to the one shown in **Figure 8**. **Please notice** that this system is linear and corresponds to a multiple mass oscillator according to the course textbook (Janschek page 236-237).

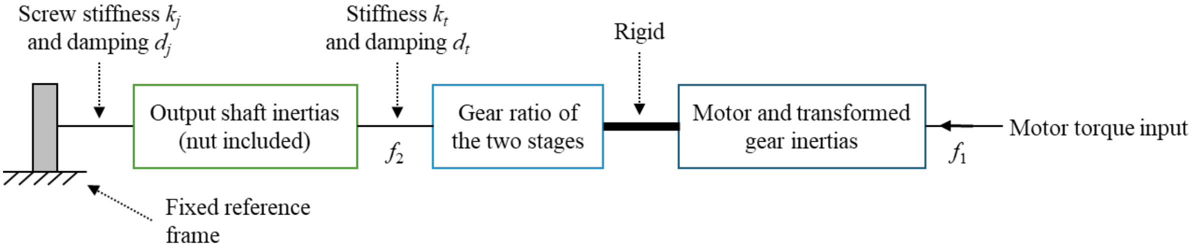


Figure 8 Simplified transmission model.

During design work, the inertia of a planetary gear stage at the input (machine) side can be estimated through formulas presented in [7]. For your convenience, the inertias for the two respective stages have been pre-calculated according to these formulas and they are:

$$J_{g1} = 6.5 \times 10^{-8} \text{ kgm}^2$$
$$J_{g2} = 5.3 \times 10^{-8} \text{ kgm}^2$$

The gear inertia of stage one is referred to the motor axis whereas **the inertia of stage two must be recalculated via the transmission ratio of stage one** to agree with the conceptual model of **Figure 8**. The **inertia of the two output shafts** should be estimated from **Figure 7** by assuming an approximate average diameter and combined length of the two pieces (the gear ratio is equal to 1 and all pieces are assumed rigid). The same goes for **the inertia of the input shaft.** By looking at **Figure 1**, you can also make an estimate of **the inertia of the nut and the socket holding the nut.**

7. Tasks

Task 1

Start the modeling with the **voltage driven** DC-motor only (**the one assigned for your group**). The following models should be developed:

- Differential equations (1)
- Block diagram (2) (Simulink)
- State-space model (3) (Symbolically in MATLAB + Simulink)
- Transfer function model (4) (Symbolically in MATLAB + Simulink)
- Multidomain physical model (Simscape)

The modeling should first be done on a generic level without numerical parameter values. Implement models 2, 3, 4 in MATLAB/Simulink and 5 in Simscape, define the model parameters in MATLAB. Show the Simulink/Simscape models and the MATLAB parameter/equation file in the report.

Task 2

Verify by simulation that the DC-motor (**the one assigned for your group**) model works as intended by applying a reasonable voltage step (considering motor specifications) on the input and studying the time-domain response in terms of current, angular acceleration and angular velocity. From the data sheet you should use for example stall torque, no-load speed, angular acceleration, and mechanical time constant to verify your model. **Make sure that your time-domain plots are scaled such that the interesting behavior is captured clearly, and make sure that the curves and the scale numbers are clearly visible. This principle should rule for your whole report.**

Justify your verification by showing that the responses are the same for all the models. If any differences are observed, they will need to be discussed.

Task 3

Develop in Simulink an angular velocity PI controller for the DC-motor using **the block-diagram model** of the motor and **show the resulting block diagram model**. Assume that you can sense angular velocity and acceleration directly. **Tune the controller to make a quick response without overshooting** to an input reference step of 12 rad/s and make sure **and demonstrate** not to violate any voltage or current limitations of the motor. However, the starting current is allowed to be **500%** of the rated current. **Demonstrate the controller's performance by time domain plots and state your controller settings**.

Task 4

Analyse the pole locations of the motor model (without control). Draw conclusions **and describe them** for a well-motivated simplification of the model. **Derive the new simplified model in terms of formalisms**:

- Differential equations (1)
- Block diagram (2) (Simulink)
- Transfer function model (4) (Symbolically in MATLAB + Simulink)
- Multidomain physical model (5) (Simscape)

Show that all four models work properly and demonstrate that in the report.

Task 5

With the given specifications of the tool, select a gear ratio for each of the two planetary gears (while assuming they have equal gear ratios). Motivate your choice. In the following, note that you should **use the notation *n* for the total gear ratio** (both gears together, and for example n_1 and n_2 for the different stages.

Hint: Electrical motors are typically associated with two different torque specifications – stall torque and continuous torque. Stall (zero speed) torque, which is the higher of the two, cannot be applied continuously due to over-heating of the motor. The continuous or rated (speed dependent) torque, on the contrary, can be applied for an extended period without risk. **Since – in our case – the nutrunner does not operate continuously we assume that we can design for utilizing the stall torque**.

Task 6

Derive a model of the complete tool and nut rotation for the rundown phase, i.e. a 4th order model, using the simplified motor model that you have developed and the previously described assumptions. **Note**: During the run-down phase, the screw stiffness **is not** involved but friction damping in the nut/screw ***is*** involved. **You must use the state vector representation suggested in Janschek on page 237**, equation 4.37, i.e.:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix}$$

Where φ_2 and φ_2 are motor and transmission angles (1: motor side, 2: tool side of the final angle gear) and **remember to use *n* for the total gear ratio**. **Note**: Since in this case the tool is considered fixed, and the nut is considered free running the angle φ_2 equals the angle θ_n of the nut.

The model simplifications according to the **Figure 8** can be applied.

Derive the following:

1. Differential equations symbolically.
2. Transform the differential equations to a state-space model.
3. Create the state space model in MATLAB (or directly in Simulink).
4. Apply the state space model in Simulink and make sure to output and log all states.
5. Simulate the model by applying a voltage step of 1 V and demonstrate for the report reader that the model works properly.

Show models 1-3 in the report. Show the simulation result (5) and demonstrate for the report reader that the model works properly **by commenting on the below three hints**.

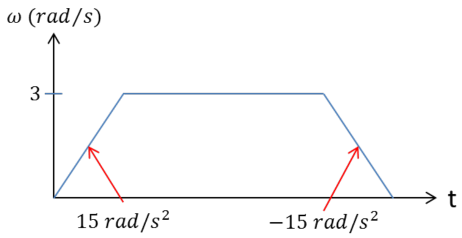
Hints:

- Study the state variable traces and make sure that they are scaled correctly relative to each other (given the gear ratios).
- The velocity saturates, but at which level, why, and is it correct?

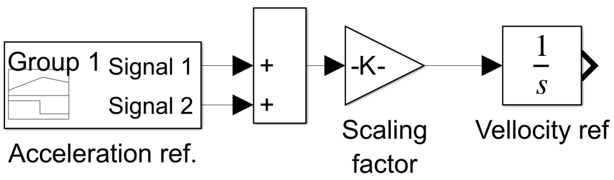
- Estimate the mechanical time constant of the system and compare with that of the motor as specified in the motor data sheet. Explain the difference.

Task 7

Develop a PI angular velocity controller for the nut rundown phase by manual (or auto) tuning (for this case, you can use the standard PID block in Simulink). The control target is to follow the below **reference signal for the nut rotation.**



Try to achieve a smooth response of the control system without overshot or steady state error. For the reference velocity it is recommended to use the below Simulink component (provided in the Canvas Assignment page as *Components.slx*). The model sets constant angular velocity after a short acceleration phase and goes to zero at 3 sec after a short deceleration phase. The scaling factor 15 (under *K* in the figure below) is used to reach the specified acceleration/deceleration levels. **The scaling factor also includes the total gear ratio *n* for the case that feedback to the controller comes from a sensor placed at the motor (realistically this would be typical). If you chose to assume that the sensor is placed at the nut side, you should remove *n* from scaling.**



Present clearly the control system response and your controller parameters. Present also the behavior of the control voltage to the motor.

Task 8

This task deals with the bolt tightening case, which corresponds to an M8 screw of strength class 8.8, pitch 1.25 mm and with free length of 100 mm (thickness of joint members). For the bolt tightening process, we assume the run-down and alignment phases are passed and that the elastic clamping phase starts at zero velocity.

Based on task 6 extend your model to include the screw/nut/joint subsystem and include the given data and the parameter data that you are supposed to calculate given the system dimensions and guidelines above. The extended model now corresponds to **Figure 8** above (including also the screw). **Note: The translational stiffness of the screw can be translated into rotational stiffness as acting on the nut (via the pitch of the screw)**. Hint: use the relations for stored energy in a translational spring and a torsion spring.

It is a good idea to use the sign (of matrix elements) and symmetry properties of the stiffness, damping and system matrices to check that the modeling is at least principally correct (Janschek p. 233, 236-237). **You must use the same generalized coordinates and states as before**:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix}$$

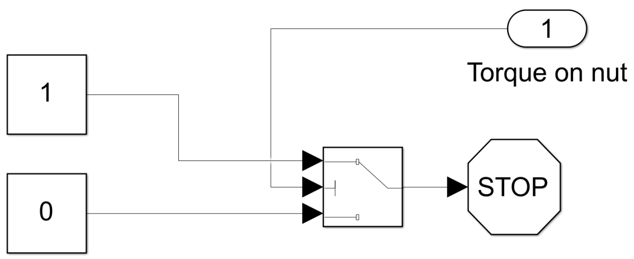
Where φ_1 and φ_2 are motor/transmission angles (1: motor side, 2: tool side of angle gear).

- Clearly present your state space model in symbolic form in your report.
- For a 24V input to the motor how large is the torque on the nut? (You can calculate it by some extra blocks in Simulink using the angular twist between gear output and nut).
- How much is the corresponding turning angle of the nut?

Task 9

Develop an angular velocity controller for the elastic clamping phase **considering the tool to be fixed**. The targeted tightening torque is 25 Nm, and the targeted tightening speed is 3 rad/s. For the bolt tightening process, we assume the run-down and alignment phases are passed and that the elastic clamping phase starts at zero velocity and should end when the targeted torque is reached. Hence, **you develop essentially a velocity controller and a torque limiter that switches the system off at the desired torque.**

To implement the controller switch-off when the targeted torque is reached you can use the below construct (provided in the Canvas Assignment page as *Components.slx*). The input is the torque delivered at the nut as sensed by the ideal torque sensor (The placement of the torque sensor can be either before or after the gearing – it is up to you). In the *Switch* block parameters, there is a threshold *T* that needs to be set, which should correspond to the targeted torque level. The stop simulation block activates when the input is non-zero.



For the velocity controller design, you should start with a P-controller, present and discuss the results (plots and controller setting), and then do the same for a PI-controller.

Task 10

Is the achieved tightening in good order with respect to the strength properties of the screw? **How large is the tightening nut angle**? Consider that good screw tightening should be such that the screw tensile stress is close to the yield strength of the screw material (stretching force in relation to the screw cross-sectional area).

If the tightening is not in good order (the force should be too high!), extend the model **in Simulink** with coulomb friction between nut and screw, thus opposing nut rotation:

$$Friction\ torque = \mu \cdot F_s \cdot r_s$$

where μ is the friction coefficient, F_s the screw force and r_s the nominal radius of the thread. F_s is easily modelled by proportionality with nut rotation via screw stiffness. Typical friction coefficients can be in the range 0.1 – 0.2. **Check again that the achieved tightening is in good order, and if not reduce the torque target to a good level. How large is now the tightening angle**?

(Note that with Coulomb friction, the system is no longer linear, since friction force can only oppose motion. The modelling we do here still works in the linear domain because the nut motion is strictly in one direction. That is, we don't expect the friction to drive the nut, only oppose its motion.)

If needed, adjust your controller parameters. Finally, show the results of your tightening process. How large is the deflection (twist) in the transmission, as seen on the load side and on the motor side respectively? Discuss the results.

Task 11

How much electrical energy is consumed in one tightening? When calculating the energy (in Simulink), assume that this energy can be estimated using the current in the motor and the known supply voltage. Assume that the battery voltage is 24 V and that the capacity is 2.5 Ah.

Assuming that the same amount of energy is consumed during the combined run-down and alignment phase, how many screws can be tightened on one battery charge?

8. References

[1] Angle Cordless Nutrunner Tensor ITB-A61-50-10. Accessible at: https://picontent.atlascopco.com/cont/external/dir/e3/16154419467_A2500001_html5_external/en-US/index.html

[2] Angle Cable Nutrunner Tensor ETV STR61-50-10. Accessible at: https://picontent.atlascopco.com/cont/external/dir/4a/381180171_C2440001_html5_external/en-US/index.html

[3] Power Focus 6000. Accessible at: https://picontent.atlascopco.com/cont/external/dir/78/18097853963__html5_external/en-US/index.html

[4] Pocket guide to tightening technique, Atlas Copco 2015, Accessible at: https://www.atlascopco.com/content/dam/atlas-copco/industrial-technique/general/documents/pocketguides/9833864801_L.pdf

[5] Datasheet for each corresponding motor can be found in Canvas or the Faulhaber website accessible at: https://www.faulhaber.com/en/products/motors/

[6] AN 183 – Equivalent DC-current in Faulhaber SC and MC. Found in Canvas or https://www.faulhaber.com/fileadmin/Import/Media/AN183_EN.pdf

[7] Roos, Fredrik, Towards a methodology for integrated design of mechatronic servo systems, Doctoral thesis, KTH, 2007, Trita-MMK, ISSN 1400-1179; 2007:07. Accessible at: http://kth.diva-portal.org/smash/record.jsf?searchId=1&pid=diva2:12432