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Model-free Fuzzy Tightening Control for Bolt/Nut Joint Connections of Wind Turbine Hubs

C. Deters, E.L. Secco, H.A. Wuerdemann, H.K. Lam, *Senior Member IEEE*, Lakmal D. Seneviratne, *Member IEEE*, and K. Althoefer, *Member IEEE*

Abstract— **In the wind turbine manufacturing industry, the bolt-nut joint tightening process is one of the core processes in the full production chain and concerned with assembling the hub body, the pitch system and the bearing unit. This operation is currently executed manually with the aid of different tools and gauges; the main disadvantages are a relatively high degree of variability and the necessity to repeat this task several times during a production run to achieve a satisfactory, final tightening torque within a specified angle range. Moreover, the bolt tightening process includes various uncertainties such as the presence of friction forces and the use of different bolt sizes with different stiffness values which make it highly nonlinear and uncertain resulting in a challenging control problem. To facilitate the development of an effective control strategy, we study the bolt tightening process and propose 4 tightening stages, namely, bolt-nut alignment, partial and full engagement and final bolt tightening. Based on the characteristics of each stage, a fuzzy controller is designed for each stage to realize the respective control objectives. A fuzzy error detector incorporating the knowledge of each stage is proposed for early error detection, making use of the input from a torque and encoder (angular position) sensor. Errors can be detected in each stage to interrupt the process and prevent any damage to the system.**

I. Introduction

Among other applications of renewable energy technologies, the power generation through wind has certain advantages because of its technology maturity, good infrastructure and relative cost competitiveness [1]. For this reason the wind turbine industry is growing rapidly and it is going to play a major role in the future national and international scene [2]. It is predicted that the wind power energy will develop to about 12% of the world's electrical supply by 2020, increasing the wind turbine sizes at the same time [3,4]. Thus, wind turbines have become more and more a mass product.

In the wind turbine manufacturing industry, the assembly is one of the core processes in the full production chain. The bolt-nut joint tightening process at the hub system is one of the core processes in the full production chain, which is to assemble the hub body, the pitch system and the bearing unit of the wind turbine. This tightening operation is still executed manually with the aid of different tools and gauges [5]: the main disadvantages of such a manual procedure are a relatively high degree of variability and the necessity to repeat this task because it can usually not be successfully accomplished the first time round. Problematic issues of screw fastening include error scenarios such as cross-threading, screw jamming, slippage as well as the requirement to apply precise sets of torque and angular values during the process.

An intelligent fuzzy logic controller overcomes these problems [6]: this work introduces an automated screw fastening control avoiding process-caused failures and aims at achieving a precise final tightening torque. This strategic approach can be adapted to other processes, as done in [7] where bolt tightening is performed by an impact wrench using neural networks. A Mamdani-type fuzzy controller uses a physical analysis of the control process [8]. In this paper the control action is described by a set of fuzzy rules and membership functions, which incorporate the knowledge and experience of the bolt-tightening operation. This model-free control approach, which is only based on the physical tightening tool uncertain attributes, realizes an effective control strategy able to handle the uncertainties, such as the variation in friction and material properties (including bolt lengths and sizes).

Compared to a fuzzy-controller, a model based approach, such as a PID controller is a well-accepted controller for industrial applications, performing particularly well for linear processes. However, when the working condition is changing (as it is the case with bolt tightening due to inherent non-linearity and uncertainties) a PID controller, with constant proportional, derivative and integral gains, is no longer able to offer an acceptable performance. A PID controller may become unstable due to uncertainties whereas a model-free fuzzy controller guarantees stability during the tightening process [9]. Hence, a model-free control approach, based on a fuzzy control scheme, is capable of integrating the practical knowledge and experience within the control loop [10,11]. Compared to the PID controller, a fuzzy system can be also used on multiple bolt systems with different system behavior, without the need of re-estimating the control parameters.

In this paper, the bolt/nut tightening problem for wind turbine assembly processes is investigated. Due to the high non-linearity, system uncertainties (different tightening angles, variations due to installation, variations in friction of bolt and different materials), and changing working conditions (such as variations in temperature, moisture and dusty environments), designing the controller is challenging.

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C. Deters (corresponding author, e-mail: Christian.Deters@kcl.ac.uk), E. L. Secco, H. A. Wuerdemann, H. K. Lam, L. D. Seneviratne and K. Althoefer are with King's College London, WC2R 2LS, London, UK.

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A fuzzy control scheme, which benefits from the experimental and practical knowledge, is proposed for the control process. Based on the investigation of the bolt/nut tightening process, a 4 stages fuzzy control system is proposed incorporating expert knowledge about the tightening process and handling the uncertainties of the system. Each stage exhibits unique characteristics that contribute to the control process.

II. Bolt/Nut joint for hub assembly

The wind turbine hub is made of three main parts, which is the hub, the bearing and the pitch system. The bearings are assembled using up to 128 bolts (depending on the wind turbine hub) to connect them to the hub. It is essential that the clamping force of each bolt/nut connection is equally distributed over all bolt connections, since the bearings mount the blades of the turbine. The blades will impart forces on the bolt-nut connections and any unbalance, across the tightened bolt/nut connections, may cause a local overload.

The assembly of the wind turbine hub is still done manually which is very labor intensive. Furthermore, during the manufacturing process, it has to be ensured that the correct bolts are used as otherwise bolts and nuts can be damaged and the final clamping force may not be achieved.

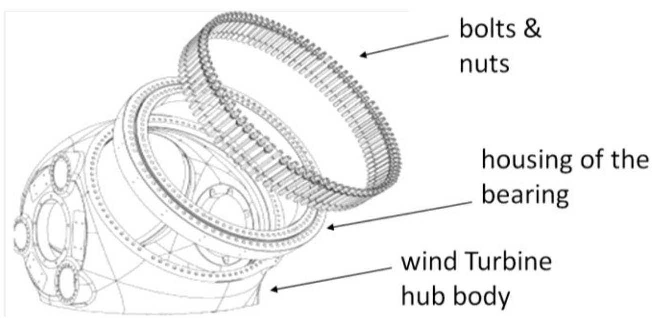

Fig. 1. Overall assembly process (picture provided by Gamesa Corp.)

III. Sequence of bolt tightening

The sequence for bolt tightening is essential for accurate tightening as well as for assembly error detection. The process has been analyzed and it can be subdivided into 4 different stages, as mentioned in the Section I. *Stage 1* regards the initial bolt/nut alignment. This leads subsequently to a partial (*Stage 2*) and full engagement (*Stage 3*) of the bolt and the nut; as soon as the nut touches the flange, the system starts *Stage 4*, i.e. the final tightening. It is aimed to tighten the nut achieving a desired clamping force through an automated process. However, each stage may suffer from various error scenarios, influencing the overall tightening process and may result in a lower than desired clamping force.

Stage 1: Bolt/nut alignment

At the beginning of the tightening process, the nut as well as the tightening tool will be placed using a robot arm, which fits the nut on the bolt using a pick and place procedure. The female and male threads meet at their starting point to prepare the actual tightening process (Fig. 2, top left panel). In *Stage 1*, the nut is touching the bolt but the tightening process has not been started yet. The requirement for the controller is to provide a slow start in order to avoid damages to the bolt or nut, in case a jamming situation arises, and to apply the required torque levels within a specific angle range. Since the assembly item is a round part, misalignments may arise too. If a misalignment occurs (Fig. 3), bolt or nut may be damaged; this means that the assembly should be promptly stopped in such a situation and the bolt replaced. The same applies if a wrong bolt connection (e.g. different thread types) is used. The target of this stage is to move the nut into a specified angle and to assure a correct alignment without error.

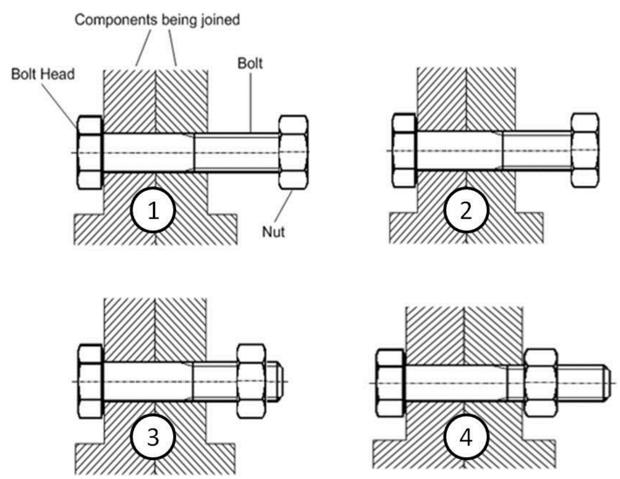

Fig. 2. The 4 stages of the bolt tightening process [13,14]

Stage 2: Partial engagement

The nut is advanced for a few degrees until both the threads are touching (Fig. 2, top right panel), requiring a slightly higher torque due to the friction caused by the threads. Possible error scenarios are a crossed nut thread and/or a crossed bolt thread or different thread types. Continuing the tightening may cause a jamming situation, leading to an undesired torque increase which needs to be detected. Wrong bolt/nut thread combinations may also be detected at this stage.

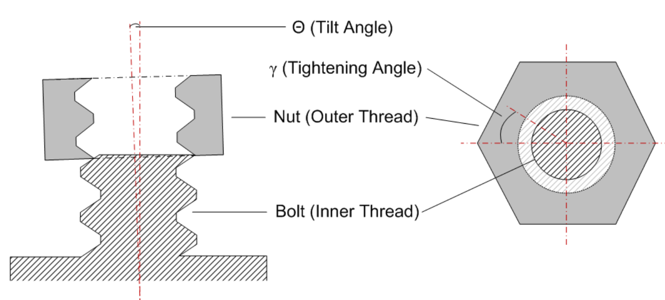

Fig. 3. Alignment problems

Stage 3: Full engagement

At this stage, the nut is running down until reaching the flange: a maximum and steady friction level occurs during the run down process (Fig. 2, bottom left panel). Possible error scenarios regard to cross threads on the bolts shaft, dirt in the thread - due to an incorrect installation - which can be detected by an unusually high torque. During this phase, the information of the angular displacement of the nut is important as it contains a feedback about how far the nut has been travelled on the bolt shaft (to estimate the correct bolt length, according to the assembly specifications). Remarkably, based on the travelled distance, an estimation about a wrong or missing washer can be made.

Stage 4: Final bolt tightening

The final tightening process is started as soon as the nut reaches the flange. Further tightening will create a clamping force between the flange and the nut (Fig. 2, bottom right panel). The torque levels as well as the final angular position of the nut are provided within the assembly specifications and they depend on the parts to assemble. Accordingly, the requirement for this stage is to apply a certain torque within a certain angle displacement without exceeding the bolt tension limit. Every bolt has a tension limit, where it applies the maximum clamping force due to its maximal tensioning and stiffness. Exceeding this limit will cause damage to the bolt and undesired performance after assembly. An error scenario would be if the nut has not reached the desired torque and angle values or if the bolt reached/exceeded the tension limit.

IV. Control Architecture

This section discusses the system architecture as well as the control strategy. Each bolt may suffer from slight variations caused by manufacturing tolerances, temperature and/or different friction. Also, different bolt types require different tightening strategies. Bolts are manufactured with different size, using various materials and they have dissimilar mechanical stiffness values. Hence, an adaptive control strategy is desirable to manage different bolts used for hub assembly.

In this paper, the Mamdani fuzzy controller has been considered, incorporating our expert knowledge on the bolt-nut tightening process through fuzzy rules. The overall structure is shown below [12]:

$$MAMD(x,y) = \bigvee_{i=1}^{n} (A_i(x) \& B_i(y)) \qquad (1)$$

where A_i and B_i are fuzzy numbers and fuzzy centroid has been used for 'fuzzyfication' as well as for 'de-fuzzyfication'.

The rules have been set as a conjunction of implications, as follows:

$$RULES(x,y) = \bigwedge_{i=1}^{n} (A_i(x) \rightarrow B_i(y)) \qquad (2)$$

In the following, each stage of the tightening process is analyzed to facilitate the fuzzy controller design. A fuzzy controller, for each bolt type for the wind turbine hub, has been derived, based on fuzzy control strategies integrating the knowledge about this 4 stages process into the control system.

For each assembly type (e.g. different wind turbine hubs) the membership functions of the fuzzy controller may require adjustments to fit the assembly specifications. Since the assembly station should be used for different bolt types, an underlying PLC system (which is required to integrate the system into a factory environment) should be able to select individual controllers and to combine them to the correct 4 stages controller. Fig. 4 shows a general set up of the system, where the PLC System is responsible for the control of the overall process. It coordinates the pick and place process, where it picks the correct nut and places it on top of the bolt by using the correct alignment. Once this task is completed, the controller calls the appropriate 4 stages tightening controller which executes the actual tightening algorithm.

The control signals are real time sent back to the PLC and this latter one drives the tightening tool. It is important to notice that this approach has the advantage that *(a)* different fuzzy controllers can be chosen by the PLC to be used for different bolt types and *(b)* several tightening tools can be integrated by calling the fuzzy controller several times.

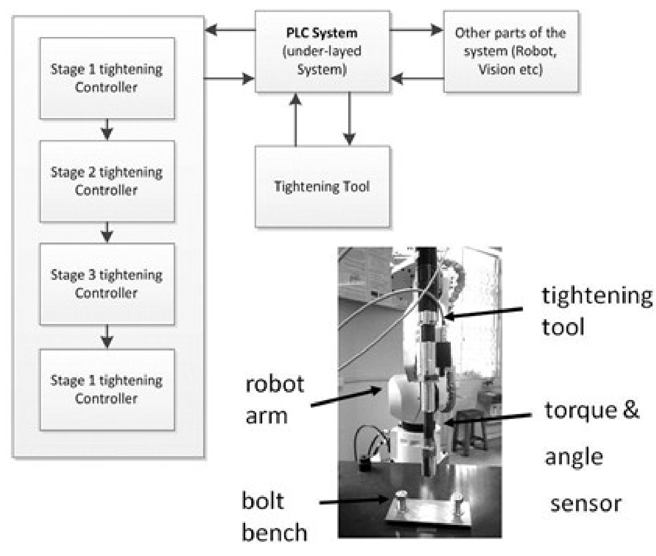

Fig. 4. Overall controller architecture

The control strategy has been implemented for a standard industrial tightening tool, using an analogue voltage as an input signal for rotational speed; this strategy may be easily modified to be used on an industrial bus system. This leads to the general generic control set up of Fig. 5. It needs to be considered that the error is calculated internally, within fuzzy control block, using defined membership functions and linguistic rules; therefore, there is no additional error feedback into the controller.

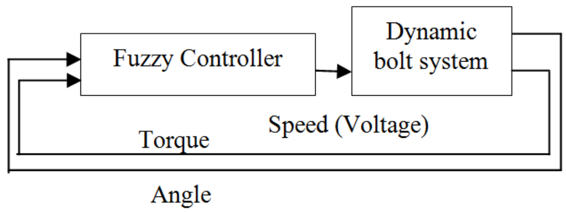

Fig. 5. Generic control diagram stage 1-4

For each stage, a 2-input 2-output fuzzy controller takes the torque and angle values, as inputs, and it produces 2 output signals, namely a control signal and an error one. The control objective is to generate an appropriate control signal to tighten the nut and achieve a desired clamping force. The error supervision signal aims at detecting any erroneous scenario of the bolt/nut coupling in order to stop the procedure before any damage may arise.

Stage 1: Alignment

A fuzzy controller with 2 inputs - torque and angle as sensing inputs - and 2 outputs (MIMO) - voltage for setting the tool's speed and error for returning the control voltage for the tool - has been designed.

The input torque contains 3 membership functions which cover *"low torque (LT)"*, *"normal torque (NT)"* and *"high torque (HT)"* conditions. The angle input contains 2 membership functions, which covers the *"operating angle area"* as well as the area where the controller is about to finish the current stage - *"desired angle (AD)"*. Similarly "*low and high angle (AL and AH)"*, as well as *"negative, zero and positive voltages (VN, VZ and VP)"* are defined.

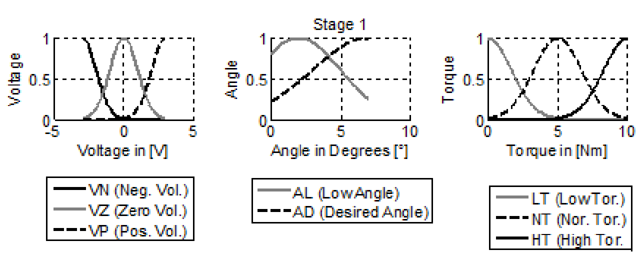

Fig. 6. Membership functions of Stage 1

The membership functions are based on Gaussian curvatures for the inputs as well as for the outputs. The rules define the control signals for the voltage as well as for the error, which is a binary value: true for the error, false for the correct operation. In an error scenario, the rules of the controller will switch the output voltage to zero and set the error output. Since the *Stage* 1 is the start point, then the tool will rotate until it reaches the starting position (where the bolt and the nut thread meet). At this point the torque will slightly increase and the control target will be satisfied. An overview of the fuzzy membership functions of *Stage 1* is shown in Fig. 6. The Gaussian curvature ensures a slow start in order to detect error scenarios before physical damage is caused. The membership functions have been combined using the fuzzy rules reported in the Table I, where MF1 and MF2 are the inputs and MF3 the output. The error output is a supervision signal (Boolean) for the PLC.

TABLE I. STAGE 1 LINGUISTIC RULES

Angle	*Torque*	*Voltage*	*Error*
AL	LT	PV	F
AL	NT	PV	F
AL	HT	ZV	T
AD	LT	ZV	F
AD	NT	ZV	F
AD	HT	ZV	T

Stage 2: Partial engagement

The fuzzy controller for *Stage 2* has a structure similar to the one of the *Stage 1*: here, the only membership function of the angle has been adapted correctly to the working range of this stage (Fig. 7). If a high torque scenario arises, the voltage output will be set to zero and an error output will be returned.

The membership functions have been linked using the same linguistic rules as shown in the *Stage 1* (see Table I). This stage is entirely angle based, since only 3-5 turns of the nut are required for the completion of the task by making sure that the nut is partially engaged in a right position.

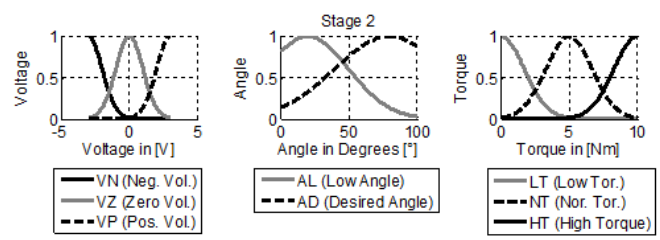

Fig. 7. Membership functions of Stage 2

Stage 3: Full engagement

This fuzzy controller contains 2 inputs (torque and angle for the sensing) as well as 2 outputs (the voltage and error signal for the action). The angle is covering the working area (run down process of the bolt's shaft) and the error is used to identify any possible high torque scenarios. A high torque scenario means that there is a cross thread on the bolts shaft causing an error during tightening. Accordingly, the membership functions of this stage have been defined (Fig. 8).

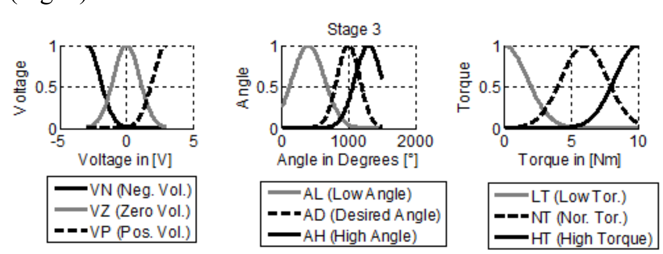

Fig. 8. Membership functions of Stage 3

Due to a higher friction, the normal torque level is slightly increased (as the nut's thread is now fully set on the bolt's thread) and furthermore the angle region has been re-defined to estimate whether a correct washer has been installed (a missing or false washer would cause a high angle scenario). A high torque scenario, within the low angle region, would be indicative for an error - as the situation of a cross thread on the bolt or a too short bolt which is installed - and will stop the tightening action. Since more membership functions have been defined for the process, the linguistic rules need to be extended as reported in the Table II.

TABLE II. STAGE 3 LINGUISTIC RULES

Angle	*Torque*	*Voltage*	*Error*
AL	LT	PV	F
AL	NT	PV	F
AL	HT	ZV	T
AD	LT	ZV	F
AD	NT	ZV	F
AD	HT	ZV	T
AH	LT	ZV	T
AH	NT	ZV	T
AH	HT	ZV	T

Stage 4: Tightening process

The last fuzzy controller contains 3 inputs (torque, tension-limit and angle for sensing), 2 outputs (voltage, to set the tools speed, and 2 supervision signals for the error and tension-limit detections) and 3 membership functions, assigned to each of the inputs. The error recognition detects if the bolt reaches its tension limit by deviation of the torque: as soon as the torque remains constant and the angle is still increasing, then the limit has been reached and the process is stopped, either with an error (if the torque has not been reached) or with no error (if the torque has been reached and the angular position is within the correct/desired range).

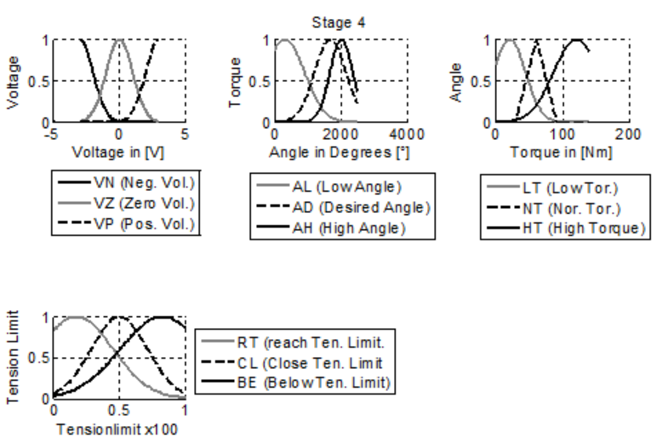

Fig.9. Membership functions of Stage 4

Furthermore, in this stage the controller is able to return to the PLC system whether the process has been successfully completed. The membership functions, for completing the tightening process, are both Booleans and they are implemented in addition (Fig. 9). We also introduce "*reached, close and below tension limit (RT, CL and BE)*".

The outputs tightening (TIGH), type Boolean, and tension limit (TL) are supervision signals set by the fuzzy controller. A set of 27 linguistic rules has been set up (Table III). These rules cover the required actions; no further rules are required.

TABLE III. STAGE 4 LINGUISTIC RULES

Torque	*Angle*	*Tension Limit*	*Voltage*	*TIGH*	*TL*
LT	AD	BE	VP	T	B
LT	AL	BE	VP	T	B
LT	AH	BE	VP	T	B
DT	AL	BE	VP	T	B
DT	AD	BE	VZ	F	B
DT	AH	BE	VZ	F	B
HT	AL	BE	VP	T	B
HT	AD	BE	VN	T	B
HT	AH	BE	VN	T	B
LT	AL	CL	VP	T	CL
LT	AD	CL	CP	T	CL
LT	AH	CL	VZ	F	CL
DT	AL	CL	VP	T	CL
DT	AD	CL	VZ	F	CL
DT	AH	CL	VZ	F	CL
HT	AL	CL	VP	T	CL
HT	AD	CL	VZ	F	CL
HT	AH	CL	VZ	T	CL
LT	AL	RT	VZ	F	RT
LT	AD	RT	VZ	F	RT
LT	AH	RT	VZ	F	RT
DT	AL	RT	VZ	F	RT
DT	AD	RT	VZ	F	RT
DT	AH	RT	VZ	F	RT
HT	AL	RT	VZ	F	RT
HT	AD	RT	VZ	F	RT
HT	AH	RT	VZ	F	RT

The final purpose of this set-up is to integrate this 4 stages fuzzy system into an industrial environment, so that already existing automation and manufacturing tools can be used. Here, a tightening tool is connected to an industrial robot arm and bolts position are detected by means of a vision system based on a Beckhoff TwinCAT 3 system [15,16]: this automation technology architecture allows the integration of MATLAB/Simulink models under hard real-time conditions, as required for bolt tightening. Also, the Beckhoff system integrates with the factory environment, including robots and vision systems, as well as the developed control strategy. Experiments were also conducted using a Phoenix Contact system.

I. EXPERIMENTAL RESULTS AND DISCUSSION

The process is a hard real time application and has been set up with a cycle time of 500µs (2 KHz). This set-up has been scaled down in a laboratory to demonstrate the functionality of the algorithm. An industrial robot (Fanuc M-6iB) is used to place the nut on top of the bolt. Once the robot provides feedback that the placement has been completed, the tightening algorithm is started. For validation purpose, 8 trials have been performed: the results of these test-runs are shown in Fig. 10, where the angular diplacement and torque time patterns are displayed for each experimental session. In the figure, each circle outlines the switching point or transition occurring from one stage to the subsequent one. The variations in angle are due to different starting positions of the bolt's thread.

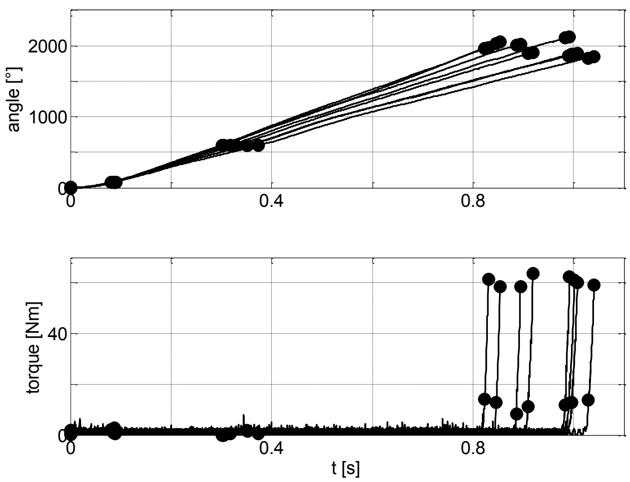

Fig. 10. Eight test runs of the 4 stages fuzzy controller

The angle area is covered by the membership functions for each stage, to ensure that the final angle reaches the desired value. The torque switching point at *Stage 3* depends on the angle in order to ensure that correct angular range has been reached as well as proper torque level is applied. These results have been further summarized in Table IV.

TABLE IV. FUZZY CONTROLLER RESULTS FOR THE 8 EXPERIMENTS

mean ±2 std (95%)			nut		
		time	**angle**	**revolution**	**torque**
		[s]	*[deg]*	*[n]*	*[N·m]*
	[init]	0.0005 ± 0.0000	0.2500 ± 0.9258	0.0007 ± 0.0026	1.1799 ± 1.3175
end of	**stage 1**	0.0870 ± 0.0064	80.5000 ± 1.0690	0.2236 ± 0.0030	1.5639 ± 1.4771
	stage 2	0.3288 ± 0.0536	600.3750 ± 1.0351	1.6677 ± 0.0029	0.4156 ± 1.6981
	stage 3	0.9330 ± 0.1538	1946.0000 ± 193.8482	5.4056 ± 0.5385	12.1083 ± 3.7438
	stage 4 [end]	0.9425 ± 0.1570	*1961.5000 ± 193.8836*	5.4486 ± 0.5386	*60.6123 ± 3.6958*

The final target of the torque has been set to 60 Nm and the angle range to 1900 degrees (based on the physical length of the bolt as well as on the washer and flange characteristics).

The controller reaches the desired value within acceptable tolerances and is also able to handle the uncertainties, such as the variation in the starting angle. In an error scenario, the controller stops the process and returns an error message and the occurring stage. The fuzzy controller performs the tightening process within less than a second and provides a high accuracy despite the system non-linearities and uncertainties.

These results have been compared with the ones of a PID controller. It is noted that the PID controller is a model based controller and may not perform as good on different bolts. For the 8 experiments, the averaged results of both controllers have been plotted in form of a Gaussian distribution (Fig. 11). As the Gaussian distributions show, the accuracy of the fuzzy controller on the desired torque level is higher than the one of the PID controller. This is due to the uncertainty of the angle, which slightly varies due to the bolt installation. The fuzzy controller can address this issue using a membership function. The final value is within an acceptable tolerance band and could be improved by adjusting the membership function.

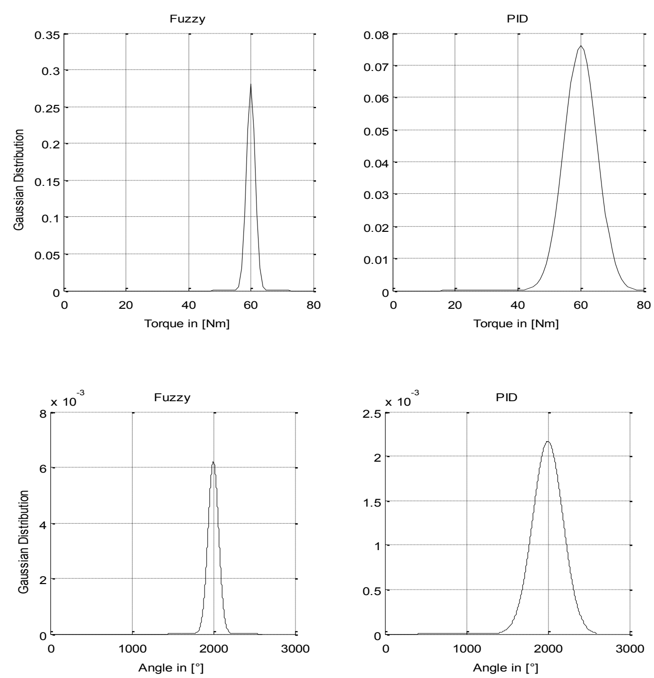

Fig. 11. Comparison of the PID controller vs. the fuzzy one (left and right panels respectively)

Error scenarios have been included in the set up to show the performance of the system in terms of error detection. In these scenarios, the controller has supervision signals which set a flag within the PLC including information about the torque, angle and stage in case of error detection. According to the same abbreviations adopted in the previous paragraphs, 5 error scenarios have been set up (Table V).

The controller detects all these error scenarios within the defined cycle time (500µs) and it automatically stops the assembly process by returning to the PLC the (a) current stage, (b) the actual values of the angle and torque and (c) if the tension limit has been reached. Thus, the controller completed the control target with a high efficiency, as shown in Fig. 11.

TABLE V. ERROR DETECTION TABLE

error type	error flag	torque	angle	stage	tension limit
misalignment	true	HT	AL	1	-
cross thread in the nut	true	HT	AL	2	-
cross thread on the bolt	true	HT	AL	3	-
washer missing	true	NT	AH	3	-
tension limit reached without completing tightening	true	LT	AL	4	RT

II. CONCLUSIONS

This paper investigates the bolt tightening assembly in the framework of wind turbine hub assembly. The wind turbine hub contains up to 128 bolts which are used to mount the bearing onto the turbine. The assembly process requires to be completed with high accuracy level. The bolt tightening process is a highly non-linear process with uncertainties (such as variation in friction, angle, environment and material). Errors need to be promptly detected at an early stage to avoid any damage and to ensure that the assembly is completed according to the manufacturing requirements and specifications.

To address this issue, a model-free fuzzy controller has been derived based on a physical system analysis. According to the analyzed uncertainties, such as variations in frictions and angles, the tightening process has been subdivided into 4 stages to include specific knowledge about the tightening operation for each of the stage and also error recognition, so that the controller can return an error feedback within the occurring stage. The controller is based on Gaussian membership functions; it ensures that the spinning speed, during the critical times of the process, is reduced and the tool runs smoothly. These results have been compared with a standard PID controller. We have shown that, overall, the new 4 stages fuzzy controller performs better than the PID one.

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