Climbing robot to perform radiography of wind blades

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Abstract. The RADBLAD project aims to demonstrate a step change in the accurate and fast in-situ non-destructive testing of wind turbine blades located offshore using remote robotic deployment of X-ray radiography at great heights to image the full thickness of a blade. This paper describes the development of the robot system that deploys an X-ray source and detector around a blade by climbing up a turbine tower. Robot design is concentrated on developing a lightweight modular robot system easily transported to test sites and assembled quickly but capable of carrying a large payload. Four tower climbing crawlers drive a ring structure (constructed around the tower) up a wind turbine tower to place an X-ray source and digital detector on either side of a blade with long arms constituted by a bridge structure. The system is actuated by fourteen electric motors, six pneumatic actuators on the ring structure and sixteen pneumatic actuators on the crawlers. The focus of the paper is on describing the remote control of these actuators via a CANopen bus and a DC power bus that aims to minimize the size of umbilical power and communication cables.

Keywords: NDT of Wind blades, Tower climbing robot, Robot control.

1 Introduction

1.1 Business need for inspection of wind blades

European Union policy targets 20% green power generation by 2021 and 40% reduction of CO2 emissions by 2030. Wind power generation is 129 GW in Europe and 370 GW globally [1] and employs an estimated 700,000 blades in operation [2]. High stresses due to wind gusts cause blade failure resulting in downtime and expensive repair. An average of 3,800 blade failures annually are attributed to poor maintenance [3] which each cost between £70,000 and £700,000. Preventative inspection is necessary every 3-4 months and maintenance every 6 months.

Most inspection is done manually by operators using ropes to abseil down to blades. There were 1726 personnel accidents from 1970 to May 2015 [4] with fatalities accounting for 45% of the total number. There is therefore a pressing need to prevent accidents by automating the inspection.

Current non-destructive testing (NDT) practice uses visual inspection, thermography, acoustic emission, or ultrasound techniques which requires skilled personnel. A EWEA survey indicates NDT technician shortage of 28,000 qualified staff by 2030 [5]. Gaining access to off-shore wind blades is difficult and expensive, currently done with large cranes on ships or by NDT technicians climbing with rope/platform systems.

1.2 Robotic solutions to wind blade inspection

The technological challenge is to increase efficiency and safety of blade inspection with specially designed robotic systems that are easily transported to off-shore Wind turbines (WTs) to perform faster automated inspections on site without requiring skilled NDT technicians. The project WINSPECTOR [6] has developed a platform that is winched up a tower to unfold an arm to bring a shearography system close to the blade. Because of blade vibration, the shearography is attached to the blade with suction cups and a compliant arm. It gives subsurface defect information to a depth of a few cm from one face of a blade.

The European Union FP6 funded project CONCEPT aimed to inspect wind turbine blades with X-Ray computed tomography with robotic deployment [7]. The X-ray system developed in 2009 was too heavy for robot deployment and the robot was built to a small-scale pilot. This concept is being developed further via an Innovate UK funded project titled RADBLAD [8].

1.3 The RADBLAD robot

RADBLAD, first of its kind, aims to meet the standard EN 50308 (Wind turbines-safety requirements for design, operation and maintenance), inspect the full thickness of a blade from one side with through transmission to give faster and better defect detection and address the skills shortage problem by being fully automated.

The project vision is to demonstrate a step change in the accurate and fast in-situ non-destructive testing (NDT) of wind turbine blades (WTB's) located off-shore using X-ray radiography. It is the best method for detecting internal defects in composite structures. It is a non-contact NDT technique and thus eliminates the need to put probes in contact and couple the sensor with the surface of a blade. The innovation comes from remote robotic deployment of X-ray radiography at great heights on large WT's to image the full thickness of a blade. Augmented with automated defect detection, classification and autonomous decision making, these advantages aim to improve the quality of inspection as compared to manual ultrasound NDT, reduce inspection time and hence reduce the cost of inspecting hundreds of blades.

The project has four key objectives:

Key objective 1: Provide access to wind blades with a lightweight modular climbing robot system easily transported to test sites and assembled quickly but capable of carrying a large payload.

Key objective 2: Position an X-ray source and digital detector on either side of a wind blade at 90° pitch angle with two manipulator arms. The modular climbing robots and

long arm structures required to reach blades must distribute loads to the wind tower to prevent the robots overturning.
Key objective 3: Adapt the X-ray source and detector autonomously to complex aerodynamic shaped blades while scanning across the width and length of a large blade. Large in-plane and out-of-plane blade vibrations will render the X-ray imaging useless unless the X-ray system moves with the blade by gripping it and using arm compliance to deal with the vibrations.
Key objective 4: Incorporate image processing methods to improve image focusing and resolution in real life radiographic images and embedded intelligence to carry out automated defect detection and classification and autonomous decision making for further inspection and intervention.

The following sections describe the realization of key objectives 1 & 2 only.

2 The RADBLAD system

2.1 The climbing robot

Fig.1 shows the robot system designed to climb a wind turbine tower (WTT) and deploy an X-ray system around a wind turbine blade (WTB). A modular RING structure composed of nine lightweight sections (trusses) is assembled around a WTT at its base while resting on axle stands. The structure is built with carbon fiber elements and weighs less than 150 kg.

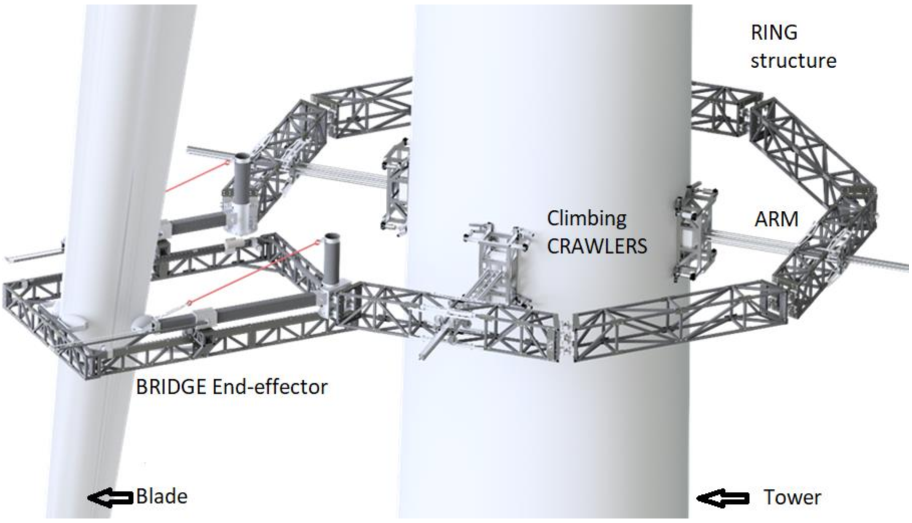

Fig. 1. The RADBLAD robot system (image courtesy of Forth Engineering)

The end-effector which enables radiography scanning of a WTB with an X-ray source and digital detector is placed on the BRIDGE structure shown in Fig.1 as accurately as possible beneath the Wind Tower Blade (WTB). Two arms of the BRIDGE open and close the end-effector with two stepper motors. The X-ray source and digital detector are moved across blade width by two stepper motors and a belt drive mechanism.

Four pneumatic AIRTECH actuators labelled as ARMS in Fig.1 are mounted on Trusses 1, 3, 5 and 7. Four tower climbing robots labelled as CRAWLERS in Fig.1 are bolted rigidly to the ends of these four ARMS. The purpose of each ARM linear actuator is to increase the traction force at the rubber track wheels of a CRAWLER by applying a force of 400N. Traction is increased further by each CRAWLER attaching to the WTT (steel construction) using force generated by a line of permanent magnets mounted in two lines along both sides of each track wheel as shown in Fig.2. Therefore, four lines of magnets per CRAWLER give a total of sixteen magnet lines for the four CRAWLERS. The drive system comprises of brushless DC motors that drive rubber track wheels with double chain transmission. Each track is attached to the central body of a CRAWLER via a hinge mechanism to allow tracks to adapt to towers of different diameters. Two pneumatic cylinders shown in Fig.2 operate at 8 bar to apply a force to correctly orientate the track and increase wheel traction.

Therefore, forces that aim to increase traction at the wheels are due to (i) magnet adhesion (ii) forces applied by four pneumatic arms (iii) force applied by two pneumatic cylinders to each track wheel.

The CRAWLERS are required to only climb in a straight line with the same position or velocity trajectory.

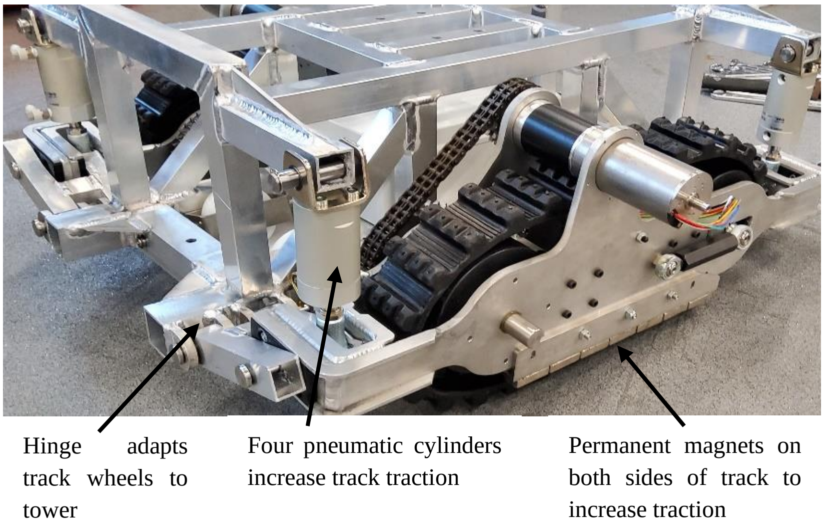

Fig. 2. CRAWLER mechanisms to adapt to tower diameter and increase traction

Two carriages mounted on Trusses 1 and 5 allow a 5° rotation of the RING in the horizontal plane to rotate the RING to make adjustments to the end-effector position beneath a WTB. The carriages are adjusted with two linear electric actuators.

2.2 Power Supply Circuit

All the devices on-board the RADBLAD robot are powered from a 24 VDC bus. The maximum current requirement is 200A, assuming all devices are subject to the maximum load at the same time. Supplying this current from the ground power over distances of 30m or more with correct cable sizes results in cable weight of more than 90 kg. Therefore, design of the power supply minimizes the power cable by supplying a 240VAC line, 32A maximum with a 3-core armored cable to the RING from the ground via a IP44 switch interlock. The AC line is split into three with a Famatel 32A three pin splitter and connected to a rack housing three TDK HFE-1600-24, 24VDC, 67A power supplies mounted on the RING truss on the opposite side of the BRIDGE to also provide a balancing load. All cables and connectors are rated IP44. The power supplies are connected in parallel to provide a 24VDC DC bus with 201A capability. The DC bus is designed with correct cable sizes to carry this current and distributed to the control devices with a cable routing scheme. Transition of the bus from one RING truss to the next is via connectors for the quick assembly/disassembly of the RING structure.

Fig.3 shows the 240 VAC 32A line to interlocked switch (IP44 32A), 30m armoured cable (IP44 32A), three-way splitter with three connectors. Three plugs (IP44) split the AC line to three TDK HFE1600 power supplies that produce a constant DC voltage of 24V, 67A each. IEC 350 connectors to 240VAC inputs on the TDK power supplies complete the AC side of the circuit.

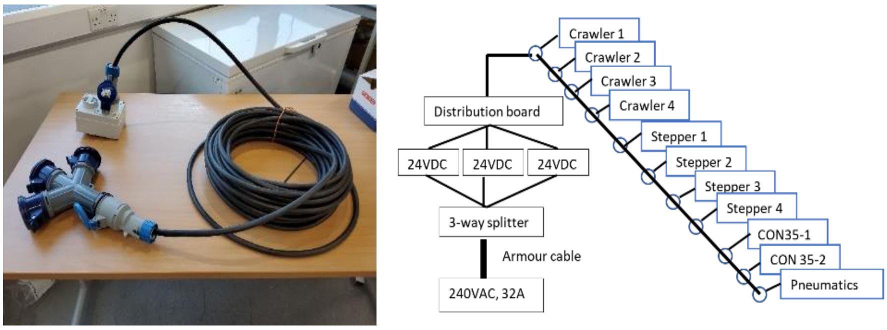

Fig. 3. Power umbilical: 240VAC, 32A line from the ground, converted to 24VDC, 201A bus

2.3 Pneumatic Supply Circuit

On the ground: 8 bar air compressor with pressure regulator reducing supply line to 6 bar.
On the robot: Two compressed air supply lines at 6-8 bar from the ground to power the four ARM pneumatic actuators and sixteen pneumatic cylinders on the four CRAWLERS. Manually switched by valves on the ground.

2.4 Communications Bus (CAN-bus)

A Speedgoat supervisory TARGET controller on the ground with a CAN IO611 module installed to read and write on the CAN bus connects to all on-board control devices with a 25m long CAN-bus cable. CAN communication speed is set at 1 Mbit/s (recommended for maximum bus length of 25m by the CiA102 standard).
A daisy chain network of the CAN-bus cable is routed around the RING and CRAWLERS to connect all on-board control devices (eight Maxon EPOS4 50/15 controllers, two Nanotek N5-2-2 controllers, two Nanotek C5-01 controllers, etc.). The last control device is terminated with a 120 Ohm resistor.

3 Control system

3.1 Control Architecture

Fig.4 shows the hardware architecture for the control system. A supervisory controller comprising of a Speedgoat real time target machine sits on the ground and controls all devices on the RING/BRIDGE and CRAWLERS via a single CAN bus operating at 1.0 Mbit/s. Simulink Real Time software is used to develop the control system.

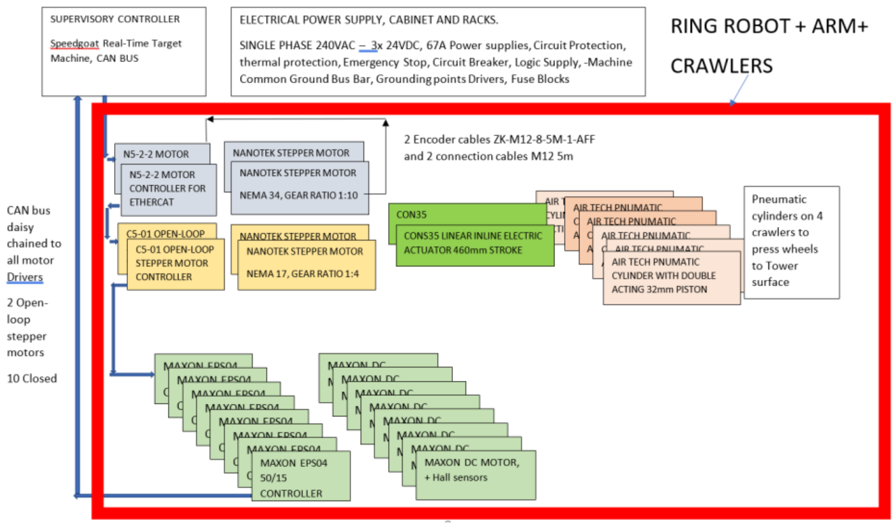

Fig. 4. Control of all on-board RADBLAD devices and actuators via CANOpen

For control purposes, the controllers/motors are divided into five sets as follows with remote control performed only for items 1-3:

1. Eight BLDC motors (two on each CRAWLER) are controlled by 8 Maxon EPOS4 15/15 devices. Position Profile mode is used to generate the same position trajectory for all eight motors with acceleration of 22 rpm/s, profile velocity of 900 rpm and deceleration of 22 rpm/s. The quick-stop deceleration is 50 rpm/s.

2. Two Nanotek stepper motors (NEMA 34, Gear ration 10:1) are controlled by two N5-2-2 controllers. These motors open/close the end-effector on the BRIDGE.
3. Two Nanotek stepper motors (NEMA 17, Gear ration 4:1) are controlled by two C5-01 controllers. These motors actuate motion of the X-ray source and detector.
4. Two CON35 Linear In-line electric actuators 460mm stroke are driven manually once by application of voltages at system setup. They enable a ±5° rotation of the RING.
5. Four ARMS are actuated with four AIR TECH pneumatic double acting cylinders. Actuated once at setup from the ground and air pressure maintained for the duration of system operation. Sixteen pneumatic actuators (four on each CRAWLER) are actuated once at setup from the ground and air pressure maintained for the duration of system operation. Two AIRTECH double acting pneumatic cylinders on the BRIDGE are controlled to deploy rollers on to a blade to stabilize it.

3.2 Control Scheme

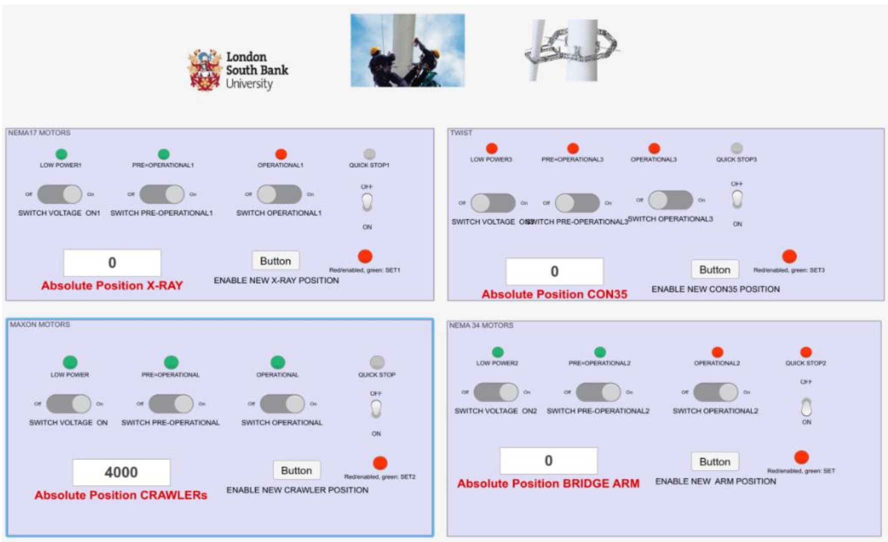

Fig. 5. GUI to control devices in Position Profile Mode. Each panel controls a set of motors

Fig.5 shows the panel to control four sets of motors. Each set is sent the same position profile with internal book-keeping to produce the correct CCW and CW rotations of the motors to produce forward/backward motion of the CRAWLERS, opening/closing of the BRIDGE end-effector and motion of the X-ray system. An edit box allows the operator to specify an absolute target position, change the target with a button press. A quick-stop switch enables emergency stops. Transitions to voltage disabled state are performed from any other state by opening the associated switch.

Each set of control devices are moved with slider buttons progressively from power disabled to a pre-operational state with power enabled (torque not applied) to operational state (motor torque applied) to follow the state transitions shown in Fig.6.

State transitions for each control device	
	Action after "command received"
0	Initialize drive
1	Activate communication
2, 8	"Shutdown"
3	"Switched on"
4, 16	"Enable operation"
5	"Disable operation"
6	"Shutdown"
7, 10	"Quick stop" or "Disable voltage"
9, 12	"Disable voltage"
11	"Quick stop"
13,14	Fault, Reaction
15	"Fault reset"

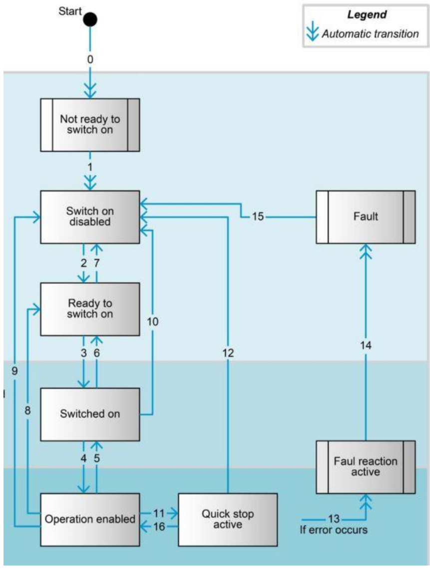

Fig. 6. State transitions: Maxon EPOS4 control devices after command received.

Four Simulink real-time state charts run concurrently to execute the control logic for the sets of actuators (CRAWLERS, BRIDGE and X-Ray systems) from the control panel shown in Fig.5. Before entry to each chart, network management commands are sent to all devices to reset network nodes and to reset communications. Entry is then made simultaneously into the four charts. The commands listed in Fig.6 are sent to the on-board control devices over the CAN bus using CANOpen protocols and respective Device ID's. The Statusword after each state transition is requested over the CAN bus and data bits are checked to ensure that the correct transition has been made. A delay of at least one millisecond is provided in the software after each command before reading the returned Statusword.

While there are four state charts that are entered concurrently after initializing all the nodes in the CAN network, only one is shown in Fig.7 for clarity to show the setting up of controller configuration parameters and switch controlled (Fig.5) state transitions and commands listed in Fig.6.

CAN messages are written to control devices using the Speedgoat CAN module IO611. Simulink Real Time block-sets are used to write messages to channels 0x600+Device ID i.e. 0x601, 0x602, 0x603, etc., for devices one, two and three respectively.

CAN messages are read from CAN identifier channels 0x580 + device ID, i.e. 0x581, 0x582, etc, for devices one and two respectively.

The status of each drive is checked after an updated Controlword (0x6040) by a request of the Statusword (0x6041). Thereby, a delay of at least 1 ms must be respected before the Statusword is checked. In the state chart of Fig.7 this is ensured by delaying transitions by 1ms with the transition condition "after (0.01, sec)".

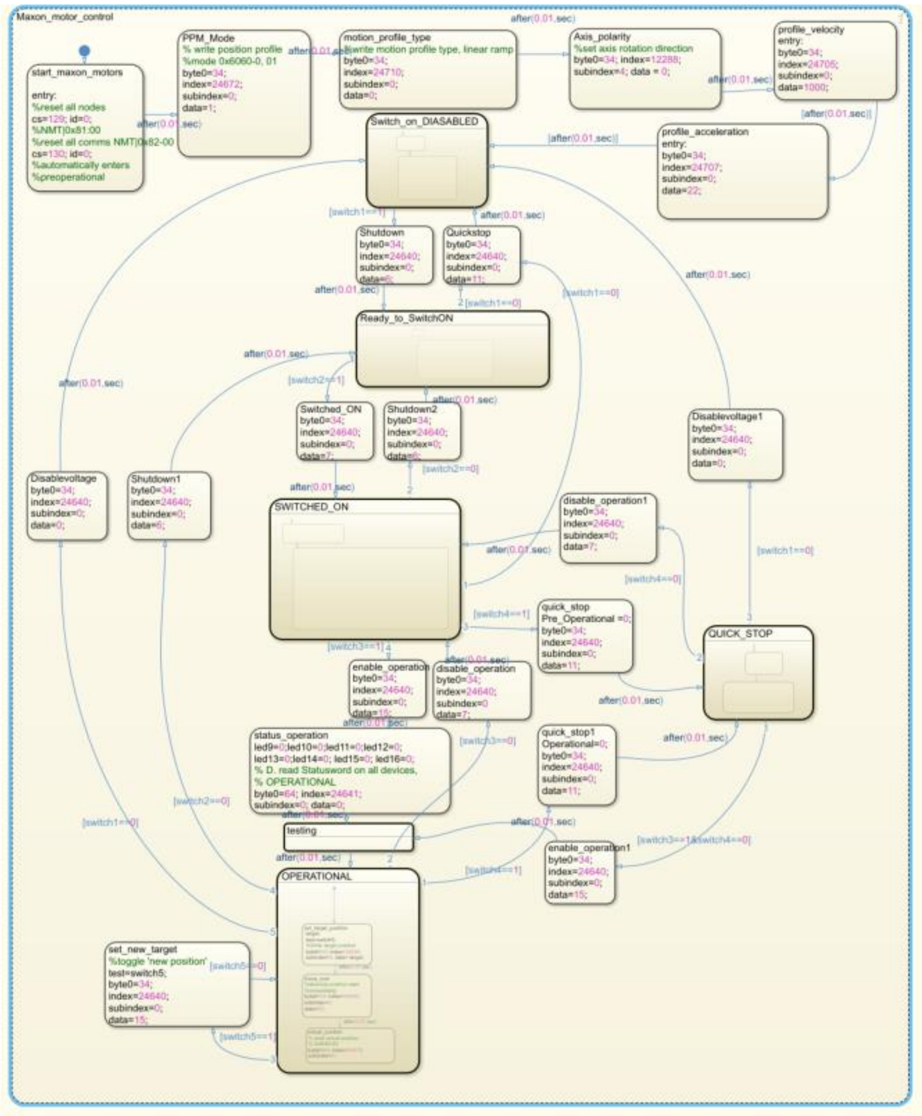

Fig. 7. Simulink real-time State chart controlling eight BLDC Maxon motors

The State chart of Fig.7 sets up the Position Profile Mode (PPM) with Command words using object dictionary index and subindex (given in hexadecimal-0x and corresponding decimal values in brackets actually used in the implementation):

1. On entry to the chart, reset all nodes with Network Management (NMT) command 000|0x81-00 (000|129-0)
2. Reset comms with NMT command 000|0x82-01 (000|130-0)
3. Set mode to Position Profile Mode 0x6060-00-01 (34, 24672-0, 1)

4. Write motion profile type, linear ramp 0x6086-00, (34, 24710-0, 0)
5. Set axis polarity, 0x3000-04-0(34,12288-4-0 is CCW and 34,12288-4-1 id CW). On the CRAWLERS, one motor must be CCW and the other CW to ensure that the CRAWLER moves in a straight line.
6. Write Target position 0x607A-00, TARGET inc (34, 24698-0, TARGET)
7. Write profile velocity 0x6081-00 as 1000 rpm (34,24705-0, 1000)
8. Write profile acceleration 0x6083-00 as 22 rpm/s (34, 24707-0, 22)
9. Write profile deceleration 0x6085-00 as 22 rpm/s

Table 1. Controlwords used in the State chart of Fig.7 to change the state of control devices

Controlword	**Object (Index-Subindex-data)**	**Object decimal values, Byte0=34 (write), 64 (read)**
Shutdown	0x6040-00-0006	34-24640-0-6
Disable voltage	0x6040-00-0000	34-24649-0-0
Switch On	0x6040-00-0007	34-24640-0-7
Enable operation	0x6040-00-000F	34-24640-0-15
Absolute position	0x6040-00-001F	34-24640-0-31
Toggle “new position”	0x6040-00-000F	34-24640-0-15
Absolute position, start immediately	0x6040-00-003F	34-24640-0-63
Read Actual position	0x6064-00-data	64-24676-0-data
Toggle “New Position”	0x6040-00-000F	34-24640-0-15
Quick stop)	0x6040-00-000B	34-24640-0-11

3.3 Testing the CRAWLER control system

Straight line motion of four CRAWLERS

Fig.8 shows the testing of synchronized straight-line motion of four CRAWLERS on the ground via the CAN bus. An absolute position profile trajectory is sent simultaneously to all four CRAWLERS. Fig.8 shows the trajectory which starts at zero position, accelerates at 22 rpm/s, travels at speed of 3000 rpm and decelerates at 22 rpm before reaching the specified target position of 3000 increments (inc). The CRAWLERS return to zero position with the same trajectory.

The climbing motion of the RADBLAD system was tested on a 3.9m diameter tower mockup. Fig.9 shows the fully assembled RING and BRIDGE end-effector.

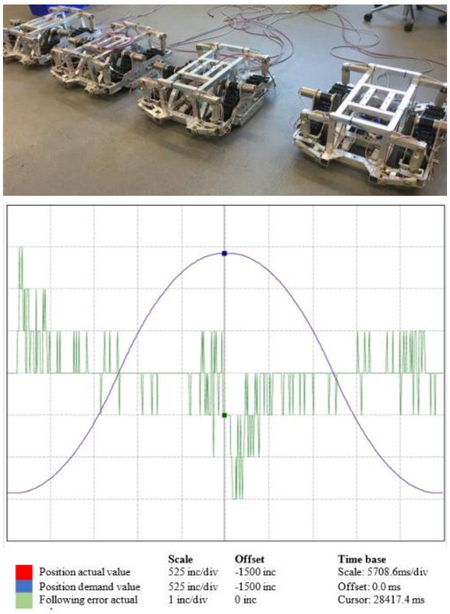

Fig. 8. Straight line motion of four CRAWLERS obtained with absolute position profile trajectory shown below

Fig. 9. RING and BRIDGE end-effector assembled around a 3.9m diameter tower

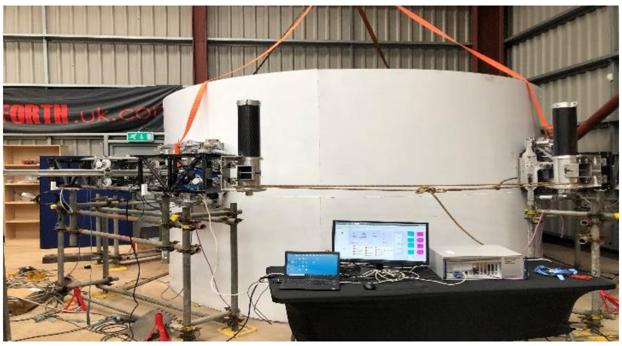

Fig. 10. Testing the climbing motion of the system without the BRIDGE end-effector

Fig.10 shows testing of the climbing motion with the four CRAWLERS lifting the RING above the scaffolding shown in the figure. Critical to the climbing motion is the traction at the rubber track wheels of the CRAWLERS. Forces applied by the four pneumatic ARMS operating at a pressure of 8 bar were found to be sufficient to provide the traction required to lift the payload.

4 Conclusions

Two key objectives outlined in section 1.3 have been achieved. A lightweight, easily transportable, modular climbing robot system has been developed to provide access to wind blades. It can be assembled quickly and is capable of carrying the radiography payload. An X-ray source and digital detector can be placed on either side of a wind blade at 90° pitch angle. The RADBLAD robot is 95% complete. The control system has been completed and tested on all actuators (14 electric motors and 22 pneumatic actuators). The power bus, communications bus and pneumatic circuits have been completed and integrated with the RING and BRIDGE structures to perform tower climbing tests. Motion testing of the CRAWLERS on the ground has been completed followed by testing of the climbing capability of the robot on a mock-up of a steel tower. The next phase of the project will take the system to a 30m tall training tower to demonstrate radiography on a blade section placed upright next to the tower.

Parallel work not reported here has developed a portable X-ray system, imaged defective blade sections and trained artificial intelligence networks to automate defect detection and classification.

Acknowledgements

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