Automation in Construction 58 (2015) 109–117

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A robotic cutting tool for contaminated structure maintenance and decommissioning

Paul Matteucci, Francesco Cepolina *

PMAR Laboratory, Dept. of Mechanics and Machine Design, University of Genova, via all'Opera Pia 15A, 16145 Genova, Italy

ARTICLE INFO

Article history:
Received 24 November 2014
Received in revised form 17 April 2015
Accepted 11 July 2015
Available online 4 August 2015

Keywords:
Cutting tool
Diamond wire
Contaminated structures
Safety robotics
Decommissioning
Nuclear power plants

ABSTRACT

With the global dependency on fossil fuels being undermined by growing prices and environmental concerns, nuclear power is returning as a solution for energy demands, however the increased cost of maintaining and updating ageing plants could render them nuclear alternative counter-economic. The development of tools specifically targeted at the maintenance field is vital to ensure the longevity and safety of existing power plants. This paper proposes a robotic tool capable of remotely cutting composite material structures. With design and engineering focused on the safety of the operator and automation, the proposed machine presents sufficient flexibility to be utilised in both maintenance and decommissioning of structures with low to medium levels of radioactive contamination.

1. Introduction

As of August 2014, 31 countries host over 430 commercial nuclear power reactors and 70 plants are in 16 countries under construction. Asia, Northern America and Western Europe have each about 120 operational nuclear plants (http://www.iaea.org/pris/). The original lifespan of a power plant was considered to be 30 years (United States. Congress. Office of Technology Assessment, 1993), however, in recent years, improvements in technology have allowed to extend the lifespan of the structures [1] to 40 years, with the possibility of further extension if the accurate maintenance is guaranteed [2]. It is however undeniable that many of the structures currently in existences are reaching a critical age, hereby they need to undergo significant maintenance and upgrades, or be shut down and decommissioned [3, 4]. This extension could be rendered counter-economic by the increasing cost of operations and a series of age-related issue such as radiation embrittlement of the nuclear power plant reactor vessel and the corrosion-induced failure of steam generators [5]. Whether or not nuclear power returns as a fundamental source of energy in the coming two decades most existing nuclear power plant sites will require some form of maintenance or decommissioning [6]. With most reactors being designed without factoring decommissioning or upgrades, these operations require extensive use of cutting machines [7] to cost-effectively remove large reactor components, making it vital to develop robotic systems which can perform such cutting operations whilst being safe, scalable and affordable. Existing cutting systems are not designed specifically for contaminated environments and employ virtually no autonomy either in the robotic platform or in the arm and tool [8, 9] with nearly all systems employing simple remote [10] control, tele-operation [11] or master/slave manipulation [12].

By encompassing modern powering, automation, sensors and enhanced remote control, this paper proposes a cutting tool designed to be used as a standalone robot, but which can also act as a mobile robot end-effector [13], which was engineered specifically to operate in both active and shutdown power plants. This was achieved by reducing the design elements which would render operation in a contaminated environment difficult, by implementing features to reduce the formation of dangerous dusts and polluting by-products, and by maximising the safety of the operator.

Diamond wire was chosen as an abrasive cutting mean due to its increase in reliability over the past two decades, the industrial success acquired in cutting composite materials in off-shore structures and the successful use of diamond wire in decommissioning the Princeton test plasma fusion reactor [14]. Reactor cores are immersed in pools of filtered water which acts as both a coolant and a radiation containment; these present the ideal conditions for diamond wire cutting tool as water cools the diamonds and prevents burning and premature degeneration of the cutting wire. When compared to alternative cutting techniques, the diamond wire system offers the advantages of a cold cutting system: low thermal impact on the structure being cut and reduced risk of sparking (unlike gas mix cutting); however, unlike abrasive cutting, diamond wire cutting creates a low volume of potentially contaminated dust by only shearing a section equal to the diameter of wire being used

* Corresponding author. Tel.: +39 331 1379 527.
E-mail address: fcepolina@hotmail.com (F. Cepolina).

http://dx.doi.org/10.1016/j.autcon.2015.07.006
0926-5805/

and not requiring additional abrasive material which needs to be removed in the case of a maintenance operation and which aggravates the contamination in the case of decommissioning [15].

2. Focus on research and innovations

The main priority of engineering a system which operates in a contaminated environment is the safety of the people involved in the operation, followed by the safety of the working environment itself. Depending on the type and level of contamination of the environment, it is likely that the robotic system will remain on site once the operation is complete and will be disposed of together with the contaminated waste or suitably decontaminated.

Based on the maintenance and decommissioning requirements the robotic system proposed is made by three main modules: a mobile platform, a manipulator, a cutting tool as working end-effector. Taking into account the heavy work made by the tool that apply very high forces to the structure to cut [16], the mobile platform has to be robust, able to overcome obstacles and able to keep stable during the cutting operations, may be after robust clamping on the structure. Platforms from the market with four separate tracks that can be tilted and raised up or down are considered for this purpose [17]. For heavy decommissioning tasks in radioactive environment, the manipulator on board the platform has to be robust, remotely controlled, waterproof in order to be washed by high-pressure water jet for decontamination; few degree of freedom parallel kinematic hydraulically powered arm is considered with a wrist that can be equipped with instrumental end effector tool [7].

The paper focuses on the design and prototyping of the most innovative component that is the cutting diamond tool purposely developed for maintenance and decommissioning tasks.

Current diamond wire tools are comprised of a simple frame upon which are mounted two or more pulleys; one which acts as a drive, pulling the diamond wire through the target structure, and at least one of the other pulleys acting as a tensioner to maintain tension on the drive pulley. Although applications in both the offshore [16] and in the infrastructures [18] have demonstrated that diamond wire is indeed ideal for decommissioning structures, these are not suitable for contaminated environments in their current form. Due to the low-technology fields in which these machines originate, they are almost exclusively hydraulically powered and deprived of sensors and automation.

Industrially available diamond wires are designed to cut either stone or carbon steel and concrete materials; the use of hydraulics as a sole mean of powering the system has various drawbacks: high flow of high pressure oil is at constant risk of leaking, requires a large and inefficient external power unit and has range limitations. It was therefore necessary to custom design a wire which would be more suitable for cutting the softer 304 stainless steel common in many core reactor components, and to engineer a solution which limited the hydraulic system to the bare essential whilst implementing remote control and extending the range of operation to that which would be safe in a contaminated environment. Furthermore, due to safety and environmental concerns [19], the design was also required to be cost effective [20] as the machine would likely be decommissioned upon completion of a campaign.

The proposed system utilises the concept of constant tension wire first patented by TS [21], where a spinning wire, held at a relatively constant tension by a pulley mounted on an actuator, is forced against a target to induce shearing. The wire is looped around two or more pulleys, one or more of which are powered.

The recent improvement in permanent magnets and consequently in electric motors means that electric motors are now sufficiently compact to be used to drive the main pulley. The use of a permanent magnet, brushless motor to drive the cutting wire, leaves only feeding and clamping functions to be powered hydraulically.

The main modules of the proposed cutting tool are visible in Fig. 1: the cutting module and diamond wire (1), it is powered by an electric motor assembled under the drive pulley; the cutting module support arm (2); the clamping module (3) [24]; the hybrid control unit (4) which encloses the communication, control and powering of system functions.

Various sensors are arranged both on the manifold and on the machine itself, providing feedback regarding the status of the machine: cutting motor absorption, feeding module position, wire tensioner position, clamping pressure, pump velocity, oil temperature, feeding circuit pressure. After the mobile robot reaches the working position the main steps of the operative cutting cycle are: arm end effector positioning guided by vision and robust clamping to the target structure, cutting tool set-up, diamond wire powering, frame sliding and cutting.

Once the main hydraulic system was eliminated, the use of a hydraulic circuit pressurised externally became redundant, and it was decided to move the motor/pump for the feeding and clamping circuits onto the machine itself. This required the hydraulic manifold, reservoir and consequently the controlling electronics to also be shifted onto the machine. It was therefore decided to centralise all of these elements into a single enclosure, together with the brushless motor electronic driver; for simplicity this was called the Hydraulic, Communication and Control Unit (HCCU).

To enhance feedback and therefore both safety and efficiency, sensors were installed on the robotic tool to monitor all the variables significant for the right development of the operation. Linear sensors were used to determine the cutting module position on its support frame, whilst most sensors were either enclosed in the HCCU (such as oil pressure, temperature, flow etc.) and all information for the cutting motor were provided to the controller from the motor driver (motor speed, power absorption, operating frequency etc.). Particular and extensive research was also dedicated to the control software, for both the embedded controller and the operator's control panel. The embedded controller provides more than just communication and control. The control software was developed to allow the system to behave as a simple tool, being controlled completely by an operator; to assist the operator with automatic cutting adjustments, or to act as a complete robotic system, autonomously performing the entire operation even if deprived of communication with the external environment. In any case the control panel interface was designed to be intuitive and easy to use for an operator used to working with traditional full hydraulic system.

3. Subsystem design

3.1. Cutting module

The cutting module is composed of four pulleys, one of which powered, which spin a diamond wire at high speed and cut the target by shearing. The wire is kept at a constant tension by one of the pulleys which is mounted on a pre-charged tensioner [16].

Tests run using traditional hydraulic actuation allowed to determine the torque required to power the drive. An experiment was setup using a 34 cm^3 hydraulic motor with a pressure sensor installed between the motor and the hydraulic umbilical. This model was chosen because it presents the largest single-motor machine currently in use and therefore the maximum amount of force expressed by a single cutting motor. The pressure was then recorded during an 80 minute cut, during which flow was maintained at a constant value 50 l/min. Return pressure was recorded at approximately 2 MPa. The recorded values for p and Δp (pressure variation across the motor) can be found in Fig. 2

By analysing the recorded data, it was determined that minimum pressure (free spinning) required by the motor is 9 MPa, whilst the maximum operating pressure was recorded at 14 MPa, during maximum surface cutting.

Torque was determined using $\tau = (V \cdot \Delta p \cdot \mu)/2\pi$ where V is the volume displacement in cm^3, $\Delta p$is the pressure drop across the motor in MPa and μ is the efficiency of the motor, 0.85 as per constructor specifications. The motor was run at optimal cutting speed; the speed was then decreased until torque was insufficient to spin the wire. The values