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Robotics Inspired Renewable Energy Developments: Prospective Opportunities and Challenges

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ABSTRACT The domain of Robotics is a good partner of renewable energy and is becoming critical to the sustainability and survival of the energy industry. The multi-disciplinary nature of robots offers precision, repeatability, reliability, productivity and intelligence, thus rendering their services in diversified tasks ranging from manufacturing, assembling, and installation to inspection and maintenance of renewable resources. This paper explores applications of real robots in four feasible renewable energy domains; solar, wind, hydro, and biological setups. In each case, existing state-of-the-art innovative robotic systems are investigated that have the potential to create a difference in the corresponding renewable sector in terms of reduced set-up time, lesser cost, improved quality, enhanced productivity and exceptional competitiveness in the global market. Instrumental opportunities and challenges of robot deployment in the renewable sector are also discussed with a brief case study of Saudi Arabia. It is expected that the wider dissemination of the instrumental role of robotics in renewable energy will contribute to further developments and stimulate more collaborations and partnerships between professionals of robotics and energy communities.

INDEX TERMS Applied robotics, automation in renewable energy, mobile robots, robotic manipulators, solar PV module, wind turbines.

I. INTRODUCTION

Human civilization perpetually depends on the energy that has become a fundamental entity behind social, scientific and economic developments. Thanks to advancements in various technological avenues, reliance and dependence on fossil fuel are getting reduced due to limited availability, growing needs and environmental concerns [1]. Therefore, since the last two decades, research and innovation in the renewable energy sector have attracted the utmost attention of the scientific and engineering communities. Primarily driven with economic growth and climate mitigation [2], it is anticipated that 100% of renewable energy may be available by 2050 [3]. This huge target can be achieved if and only if novel and innovative development, adaptation, commercialization and deployment technologies are presented by the scientific community to strengthen further the applied research associated with the renewable energy sector [4]. Consequently, there is an immense need to critically analyze the performance and viability of the existing processes to automate these using recent cutting edge technologies.

Robotics is an applied domain whose radius of applications is getting incredibly wider owing to its multi-disciplinary nature [5]. Robotics engineering is now being acknowledged as a dedicated branch of engineering [6]. Robots are extensively used in agriculture [7], food [8], [9], medical [10]–[14], cognition [15]–[18], nuclear [19], space [20]–[22], aerospace [23]–[25], under-water [26], [27], industrial [28], [29], oil and gas [30], textile [31] and in other tracking [32], [33] applications. International Federation of Robotics (IFR) is considered as a primary resource of providing data on the worldwide use of robots. IFR classifies the robots into two broader categories; industrial robots and service robots. In autumn 2019, IFR released the latest statistics of robots

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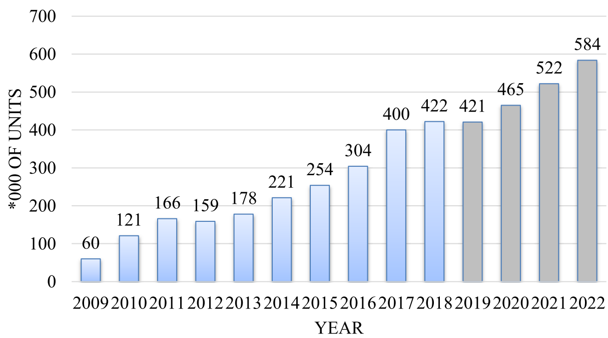


FIGURE 1. **Global annual supply of robots for industrial setups during 2009-2018 and prediction until 2022 [34].**

stating a 6% increase in global robot installations in 2018 with a record sales value of 16.5 billion USD [34]. It is reported that a greater trend toward automation is the primary reason for the tremendous increase in the demand for industrial robots particularly since 2010. The speculated average yearly growth rate of industrial robots during 2019-2021 is 14%, with new installations of around 2.1 million setups round the globe. The estimated annual supply of industrial robots with a forecast in the coming years are presented in Fig. 1. Automotive, electrical/electronics and metal/machinery sectors are the top three industries w.r.t. deployment of industrial robots. Statistics for robot usage in the renewable energy sector is not available as of to date.

This paper is related to applications of robotics in the renewable energy domain. The relationship between robotics and renewable energy can be described in two folds; renewable energy resources can be used to meet the power requirements of the robots [35] while on the other side, robots find enormous potential in renewable energy technologies [36]. The former aspect is reviewed in detail by the author in [37]. It is highlighted that the power system of a robot can be based on solar [38], [39], wind [40], [41] and biological energy [42], [43]. In contrast, the present review deals with the later aspect. Robots have the potential to completely transform the traditional methods in the renewable energy sector [44]. They can precisely perform common industrial tasks like machine tending [45], grasping [46], cutting [47], drilling [48], polishing [49], painting [50], welding [51], assembling [52], palletizing [53], packing [54], moving [55], cleaning [56], sorting [57] in addition to automating assembly lines [58] and pick and place operations [59]. Most of these operations are essentially required in the renewable energy industry, e.g. during manufacturing, assembling, installation, inspection and maintenance of panels and wind turbines. In combination with computer vision [60], image processing [61] and control [62], [63], robots offer intelligent and automated solutions to improve quality and enhance productivity with adaptability and efficiency at reduced costs [44] and thus demonstrate a central role in making renewable energy resources more competitive.

The paper is structured as follows; Section II discusses fundamental concepts behind robotic manipulators. Section III and Section IV respectively classify robots for solar and wind sectors and present recent and prominent state-of-the-art developments. Section V deals with the contributions of robots in other domains of renewable energy, namely hydro energy and bio-energy. Section VI briefly outlines the challenges and explores further opportunities for robotics in the renewable energy sector. A brief case study of Kingdom of Saudi Arabia (KSA) is presented in Section VII. Finally, Section VIII comments on the conclusion and highlights the potential benefits of this comprehensive review.

II. KEY CONCEPTS BEHIND ROBOTIC MANIPULATORS

Robots can be generally classified into manipulator-type robots [64] and mobile robots [65], [66]. The former category is more common in the renewable energy sector. Understanding of the fundamental concepts behind robotic manipulators is important to adapt a general-purpose robot for a specific application [67]. These concepts include but are not limited to [68]; kinematics, dynamics, control, trajectory planning, cost, workers' safety, ease in Operation and Maintenance (O&M), etc. Some of these concepts are detailed below:

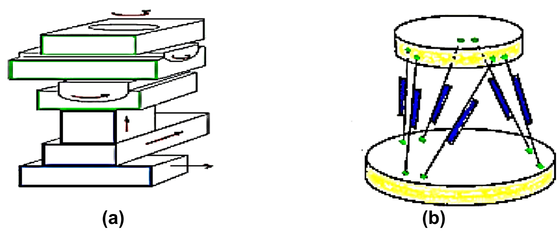


FIGURE 2. **Robot categories (a) Serial stage (b) Parallel Kinematic Manipulator (PKM).**

A. KINEMATICS AND DYNAMICS

A robotic manipulator can be kinematically based on serial or parallel mechanisms. The serial robots offer a significant percentage of robotics-based solutions in the renewable energy sector (See Fig. 2a) [69]. However, the robots with Parallel Kinematic Manipulator (PKM) structure (Fig. 2b) have been recently introduced in the energy sector.

An example of a platform centered on a 6-DOF (Degree Of Freedom) serial link articulated robotic manipulator is shown in Fig. 3. The framework named as AUTonomous Articulated Robotic Educational Platform (AUTAREP) has been developed for educational and research purposes. The actuation system consists of six precise DC geared servo motors while the sensing system comprises of position encoders, a force-sensing resistor and an on-board camera. Applications of the platform implementing frequently encountered industrial tasks, e.g. pick and place and sorting are reported in [70] while software and hardware architectures of the platform are presented in [71].

On the other hand, PKM is an ideal choice for light-weight applications with the robotic end-effector offering low inertia and high stiffness and high payload capacity. However, the

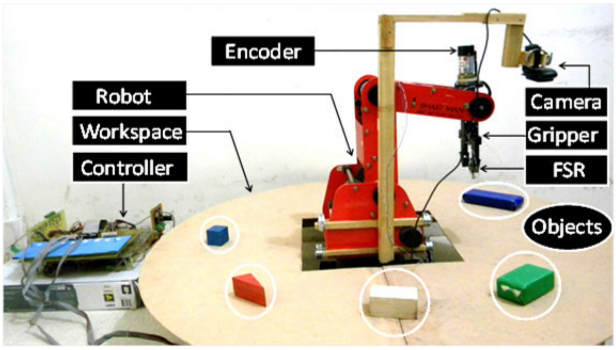


FIGURE 3. AUTAREP – An open-source pseudo-industrial framework [70].

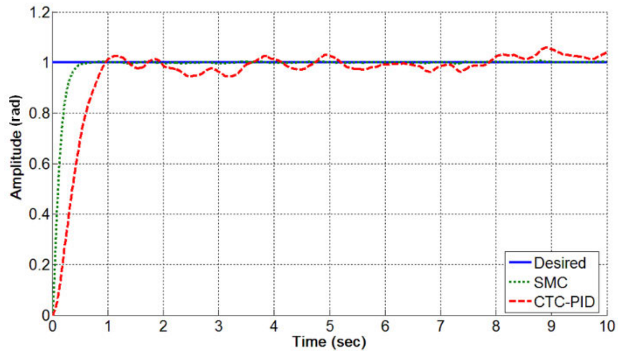


FIGURE 4. Step responses of a linear control law (Computed Torque Control CTC with PID) and a modern control law (SMC) depict that later demonstrates better tracking performance in the presence of disturbances [79].

workspace envelope of a PKM is relatively smaller when compared to serial manipulators [72]. A popular example of PKM is FlexPicker, also called as 'Delta' robot [73]. The robot accounts for 3-DOF configuration restricted to move only in translation.

One of the preliminary steps to realize a robotic system in an applied context is the modeling of its kinematics and dynamics behavior [74]. Modeling can be based on Denavit-Hatengerg (D-H) parameters or other representations, including Hayati-Roberts (H-R), screw theory, geometrical, Lie Algebra, etc. A detailed review of the modelling of robotic manipulators is reported in [75]. The forward kinematics of the AUTAREP manipulator is derived in [76], while the inverse kinematic model is reported in [77]. Unlike serial manipulators, the direct solution in PKM cannot be derived analytically. For a PKM, a vector loop equation is formulated for each limb considering a closed-loop kinematic chain.

The extension of a robot's kinematics is the development of dynamic models mainly used for acceleration analysis [78]. The dynamics equations can be formulated based on several methods like Newton-Euler, Euler-Lagrange, recursive Lagrange, D'Alembert principle and Kane's equations. The first two approaches are more commonly followed. The dynamic model of the AUTAREP manipulator based on the Euler-Lagrange method is reported in [79]. For PKM, explicit equations representing system dynamics are complicated due to the closed kinematic chain in the manipulator. One way to build a computationally inexpensive model is to use the principle of virtual work.

B. CONTROL

Analysis and investigation of robotic manipulators in an applied context has highlighted the immense need for complex strategies for control and dexterity [80]. Systematic reviews on current and emergent control strategies for robotic manipulators are reported in [81]–[83]. Since the last three decades, industrial processes have been classically controlled based on linear control laws [84]. Proportional Integral Derivative (PID) implementation of AUTAREP is reported in [85] while Linear Quadratic Regulator is presented in [86]. The research community has lately applied advanced control strategies based on modern and nonlinear control laws [87] on multi-DOF robotic manipulators to deal with uncertain parameters and disturbances [88]. The control laws based on Sliding Mode Control (SMC), Passivity Based Control (PBC) [89], Model Predictive Control (MPC) [90] and [91] have been implemented on AUTAREP manipulator. A typical response is illustrated in Fig. 4, which shows the ability of a non-linear control technique to handle disturbances.

III. ROBOTS IN SOLAR ENERGY SECTOR

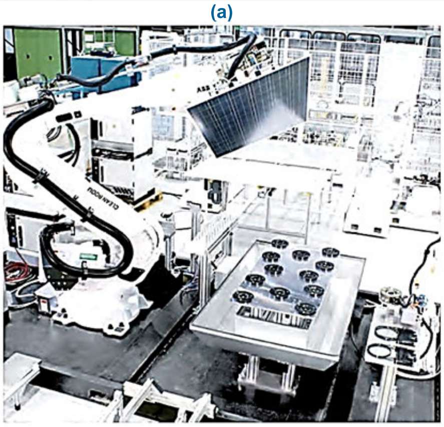
Robots find enormous potential in production, handling, installation, inspection and maintenance operations in the solar sector [92]. In a typical solar system manufacturing, robots can automate various processes involving silicon modules, silicon ingot, solar cells and silicon wafers. The role of robots in the solar energy sector can be broadly categorized into two domains; (a) Handling cells and wafers and (b) installing, assembling and performing O&M of solar panels.

A. ROBOTS FOR HANDLING CELLS AND WAFERS

Robots are best suited to handle silicon wafers and solar cells owing to their ability to handle delicate components. Compared to the performance achieved with manual procedures, robots assemble various solar components in a precise and gentle fashion since they can accurately demonstrate user-defined speeds while ensuring reliability and repeatability. A prominent example of efficiency improvement in solar cells using the application of advanced technologies is '*p-type monocrystalline perc solar cell*' by a company *Jinkosolar*, which proclaims itself as the largest manufacturer of Photovoltaic (PV) arrays. Marking a new world record, the company improved the efficiency of the cells from 22.78% to 23.45% with the help of technologies like mobile robots, intelligent mobile devices and the Internet of Things (IoT) in the manufacturing chain.

Various robots have been reported in the scientific community for cell and wafer handling. IRB Flex Picker, by ABB Inc., is an industrial robot used for sorting and handling of silicon wafers and solar cells. It is also applied for loading

(a)



(b)

FIGURE 5. Commercial robots for cell/wafer handling [92], [93] (a) IRB 360 for sorting of wafers and loading/unloading of cells (b) IRB 4600 for pelletizing/depolarizing and loading/unloading applications.

and unloading of solar cells production units (Fig. 5a) and is considered as the fastest robot in terms of executing pick and place cycles per minute [92]. It offers maximum handling of 15g at 200 cycles/min. The cycle time depends upon the tool, gripper, path radius, etc. It is an inverted mounted robot with 120-145Kg weight having a payload capacity up to 8Kg. Another functionally similar robotic manipulator used for pelletizing/depolarizing, handling and loading/unloading applications is IRB 4600 (Fig. 5b). It can handle heavy payloads of up to 20Kg with flexible mounting capability. Another prominent name of the global mechatronics solution provider is Stäubli Corporation, which offered 4-axis and 6-axis robotic manipulators to handle all crystalline (c-Si) production processes. Examples of the robotic arms include ultra-precise 4-axis FAST picker TP80, SCARA (Selective Compliance Assembly Robot Arm) TS and 6-axis TX manipulator.

Cutting of solar cell modules and edge trimming is another important step in the production of solar panels. IRB 6640 series of ABB industrial robots offer high precision to achieve this step in the shortest cycle time. This series of robots provide a reach from 2.55m to 3.2m with a handling capacity from 130Kg to 235Kg. Further, for the preparation of ribbons and soldering of solar cell modules, IRB 1600 series of ABB robotics is an efficient deal. While ensuring quality and reliability, the robot offers 1.2m to 1.45m reach and can handle 6Kg to 10Kg payloads with almost up to half-cycle time than other competitors [92], [93]. Adept Robotics offers a similar solution for solar panel production. Overhead mount robot, Quattro s650, is a parallel robot that offers the largest work envelop and handles solar cells at the highest speed with minimum breakage level [94]. It can handle a payload of up to 6Kg. Adept Inc. further facilitates solar panels' cutting, sorting, assembly, testing, loading/unloading, and inspection with its Viper and Cobra modules [95].

In an attempt to strengthen the manufacturing of solar cell arrays with a focus on the space industry, researchers from the Robotic Institute of Shanghai Jiao Tong University have developed a robotic platform [96] to automate various processes. The platform can auto-dispense and can auto-laydown with a three DOF mechanism (see Fig. 6) to handle the large sizes of arrays with high precision. The system effectively takes care of adhesive thickness, avoids bubbles formation and offers stainless production.

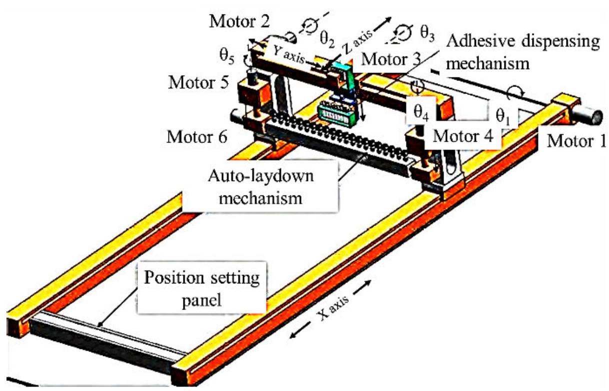


FIGURE 6. CAD model of a robotic system for auto-dispensing and auto-laydown of solar cells for space industry [96].

PV cells are covered with a protective glass coating, whose capability to generate electricity is constrained if dust accumulates on the modules [97], [98]. A study reported in [99] explored the relationship of dust thickness and solar intensity on the power output of a PV module. The experimental setup consists of a fixed tilt angle of 16°. The results in the form of power output corresponding to solar intensities of 400 W/m^2 - 700 W/m^2 for various dust thickness were presented. It was noticed that degradation in the PV performance decreased with the increase in solar intensity. The reduction in power output was negligible at 700 W/m^2 compared with a 25% reduction at 400 W/m^2. Another study [100] investigates the effect of varying tilt angles on the transmittance of plates due to atmospheric dust for around one month. Figure 7 presents the results of this experimental study showing eight different degradation curves corresponding to tilt angles from 0-90° w.r.t horizontal. The results dictate that fractional degradation in transmittance is a strong function of dust accumulation and tilt angle in addition to the exposure period and climate conditions of the site. Other recent studies

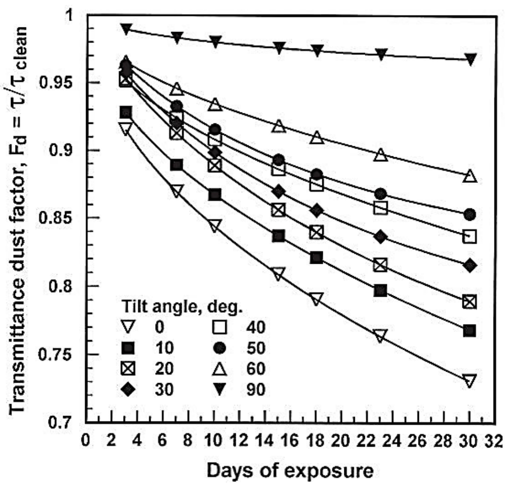


FIGURE 7. Effect of dust on the transmittance of PV glass plates versus the number of days of exposure to dust [100].

TABLE 1. Comparison between water wash and robotic wash cleaning of solar panels (↑ indicates 'High', ↓ indicates 'Low' and – indicates Nil).

Parameter	Water Wash	Robotic
Operational cost	↑	↓
Labor cost	↑	–
Workers' safety	↓	↑
Fuel consumption	↑	–
CO_2 emissions	↑	–
Water wastage	↑	–
Air pollution	↑	–

exploring the degradation rate of transmittance as a result of deposition of dust and various contaminations are reported in [101]–[107].

Rain helps in cleaning the panel, provided they are slanted downward. However, in desert regions, sand and dust are accumulated on the surfaces [108]. Cleaning by human laborers is not a viable solution due to the remote location of panel facilities and harsh weather. Table 1 presents a comparative summary of cleaning strategies based on water-wash and robotic mechanisms. Autonomous robots with onboard state-of-the-art sensor technology have the potential to replace the traditional method of manual cleaning of the modules. The choice of a particular solution depends on the application domain, geographical terrain, desired performance and economic factors [109]. A comprehensive study reported in [110] mentions that automatic cleaning is an optimal choice for panel cleaning on Earth as well as on Mars.

Figure 8 illustrates a robotic cleaner conceptualized and realized under the supervision of the author. It is a custom-designed and indigenously developed wheel-based mobile robot equipped with a roller brush, ducted fan and blower fan.

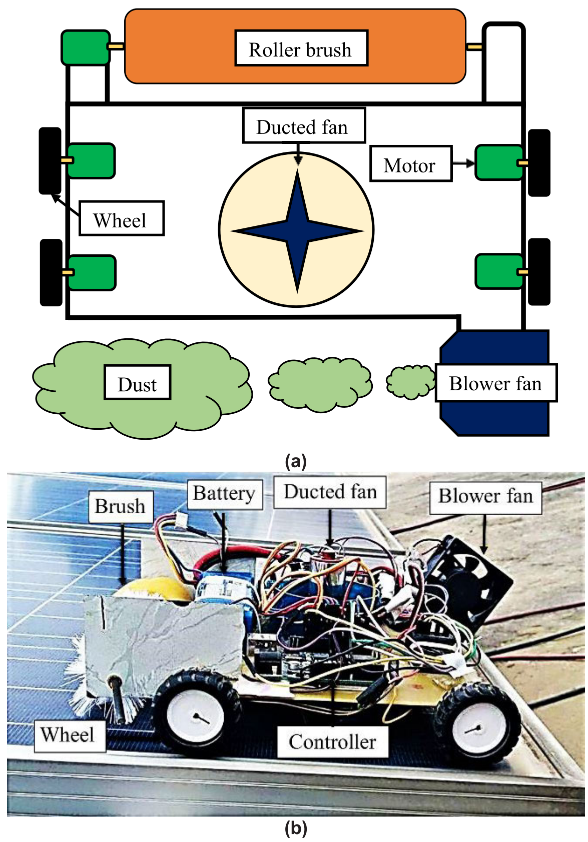


FIGURE 8. Robotic cleaner (a) Schematics (b) Developed prototype [112].

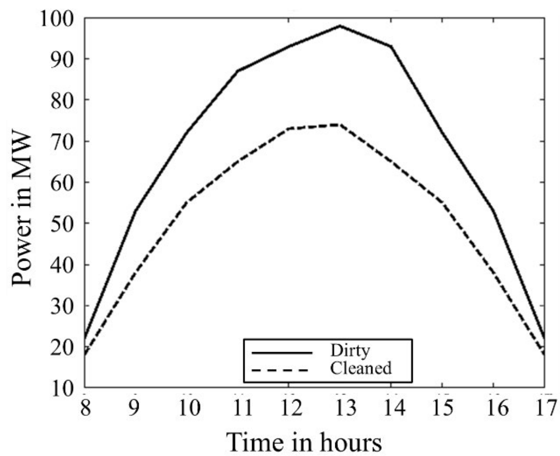


FIGURE 9. Experimental results demonstrating the cleaning effect on the power generation ability of a solar panel [112].

The cost of the cleaner is as low as 50$. Figure 9 demonstrates the potential of the robot in cleaning PV modules.

Recently, mobile robots are being equipped with a multi-DOF robotic arm for cleaning of PV panels. A prominent example is of 'Solar Panel Cleaning Robotic Arm' (SPCRA), which is a 4-DOF mobile manipulator with two prismatic and two revolute joints [111]. A single unit containing a wiper, an air blower and a water sprinkler is housed on the

TABLE 2. Energy consumption of SPCRA for one-time cleaning [111].

Action	Average current (A)	No. of cycles	Total time consumed (sec)	Energy consumed (mAh)
SPCRA platform motion on guide rail	0.385	3	18	5.775
ARM motion (rotatory)	0.65	6	8.25	8.9375
Base platform rotation	0.41	1	6	0.6833
Cleaning head	0.39	12	24	31.2
Total				46.5958

TABLE 3. Popular solar panel cleaning robots.

Robot	Company	Cleaning Mechanism	Salient features		Picture	Reference
GEEKO	Serbot	Water	Max. cleaning capacity	$576m^2/h$		[256]
			Max. speed	$9.6m^2/min$		
			Dim. LXWXH	1800X1250X432		
			Weight	63Kg		
			Water consumption	0.5-3.0 l/min		
E4	Ecoppia	Dry	Dust removal	99%		[257]
			Energy independent	100% solar		
			Cost-effectiveness	18 months return on investment		
Solar Cleaning Robot	Miraikikai	Dry	Weight	17Kg		[258]
			Typical cost-effectiveness	80% reduction compared with manual cleaning		
			Power requirements	Li-ion battery provides 1.5 hrs. of usable time per 3-hr. battery charge		
RAYBOT	Ecovacs	Dry	Cleaning speed	5 solar panels/hr.		[113]
			steep rooftops up to	55°		
			Power requirements	Battery-powered		

end effector. Experimental trials conducted on 50W solar panels demonstrated efficiency enhancement of 9.1%, which can be further improved to a significant extent using modules of a higher rating. Table 2 presents the results of the energy consumption of SPCRA for a one-time cleaning operation.

Other examples of robots cleaning solar panels include GEKKO, E4, RAYBOT, etc. GEKKO is a mobile robot that is claimed to be four times more efficient compared to manual cleaning. The robot can steep rooftops of up to 45° and is teleoperated by a joystick. Unlike GEKKO, another robot E4 performs cleaning operation without water using controlled airflow and microfiber to flick away soil. The gravity ensures that soil is wiped in the downward direction and off-panel rows. The robot has a dedicated onboard solar module to meet the power requirements. Thanks to the World Wide Web, the robot can be controlled anywhere from the globe and weather data is available from onboard sensors. Another autonomous robot based on dry-cleaning has been designed by Miraikikai Inc. Japan. It is a small wheeled robot that is powered with batteries and is equipped with advanced sensory mechanism and rotating brushes to remove sand and dust. RAYBOT is also a dry-cleaning robot presented by Ecovacs- a household robotic innovator. It is essentially a Roomba robot [113] equipped with brushes, vacuums and a blower to wipe off sand. The robot has been successfully tested in China and California before its launch. Table 3 lists

(a)

(b)

FIGURE 10. MOMO Robotic System – Handling of PV modules [120]: (a) Transportation (b) Assembly.

notable solar panel cleaning robots. Other examples are reported in [114]–[118]. Interested readers are referred to a recently conducted review [119] reporting state-of-the-art on robots for cleaning PV panels.

B. ROBOTS FOR INSTALLATION, ASSEMBLING AND MAINTENANCE OF SOLAR PANELS

Robots are now becoming an integral part of the solar panels industry. Due to the complex design of the panels and associated stringent requirements in terms of precision, consistency and delicate nature, robots are a natural choice.

Robotics community has offered numerous solutions to facilitate installation, assembly and O&M of solar panels. German companies Kiener Maschinenbau GmbH and PV-Kraftwerker jointly realized a solar plant installation robotic system named MOMO, which provides efficient productivity and offers reduced risk factors [120]. The system, shown in Fig. 10, offers cost-effective assembly, maintenance, cleaning and dismantling of solar plants. It can be operated in difficult terrains and weathers for extended operational periods. It is equipped with a gripper for automatic assembly of PV modules with the capability of numerous cycle repetitions. The robotic system can stand-alone cover 70Km of distance during an assembly operation.

KUKA Systems has offered state-of-the-art production lines for solar panel manufacturers (Fig. 11). The pioneer assembly line installed in 2011 in Canada facilitated

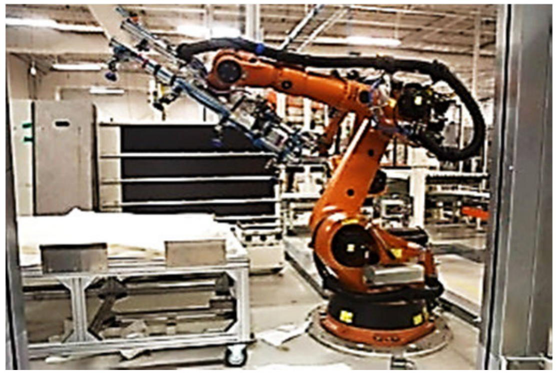


FIGURE 11. A KUKA robot assisting in the production of solar panels [123].

trimming, framing, testing and packaging of PV panels employing three automated lines with five robots for each line [121]. Such assembly lines take care of all production stages of solar panels of different types and dimensions. Besides, KUKA offers a whole range of robotized solutions for a variety of solar module manufacturing, cell and wafer handling, lamination, crystalline module simulation, etc.

National Renewable Energy Laboratory of the US, in cooperation with Spire Corporation, has completed a project for automated production line for solar modules during 2003-2007 named NREL's Photovoltaic Manufacturing R&D (PVMRD) [122]. The project comprising of three phases included the realization of large-area PV arrays (5ft by 12 ft), development of automated production tools for large scale manufacturing and design of solar modules simulator. Robots with various configurations were designed, tested and employed for the project. An operational scenario is sketched in Fig. 12, where a pair of SCARA robots is used to install bus ribbons and diodes. The complete module is processed in three parts using a conveyor belt mechanism so that moderate-sized robots can be used.

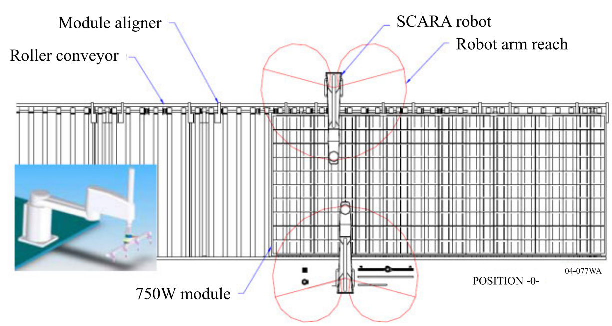
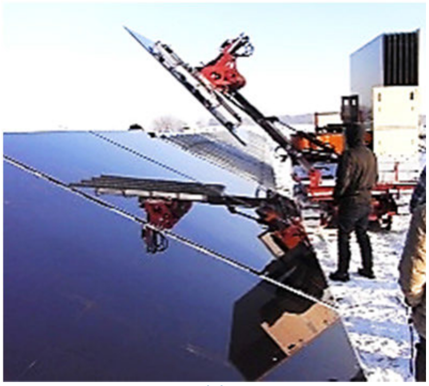


FIGURE 12. String buses operation inspired by the use of two SCARA-type robotic manipulators [122].

Robots are serving the installation and construction of solar PV plants making the process safe, fast and more economical. Figure 13a shows a mobile robotic platform installing a solar panel conceived by a German company Gehrlicher [124]. With the ability to install solar panels in all weather



(a)

(b)

FIGURE 13. Robots for installation and construction of PV panels (a) Gehrlicher's robot [124] (b) Alion's automated busing system [125].

conditions, the robot conveniently works with ground-mounted panels. Another automated system for O&M of solar PV plants by Alion Energy is illustrated in Fig. 13b. The system has a rover that installs panels. A solar-charged battery-powered and mobile-controlled cleaner named 'Spot' performs wet or dry cleaning.

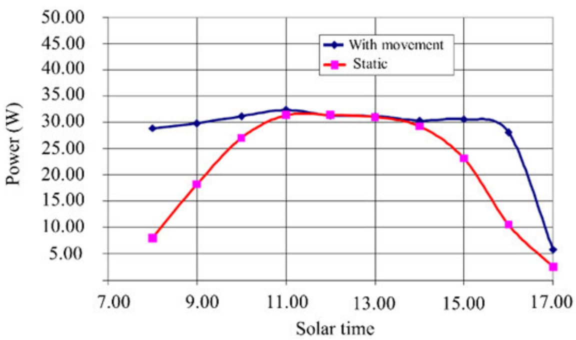


FIGURE 14. Comparison of power generated by a static panel and a moving panel [133].

Solar tracking systems find enormous potential in solar energy applications, as highlighted in [126]–[130]. Tracking of the panels is important since the amount of energy harnessed by a panel heavily depends on its orientation w.r.t. the sun [129], [131]. Also, the tracker helps in uniform distribution of solar flux over the surface of the collector [132]. Figure 14 presents a typical comparison of power generation

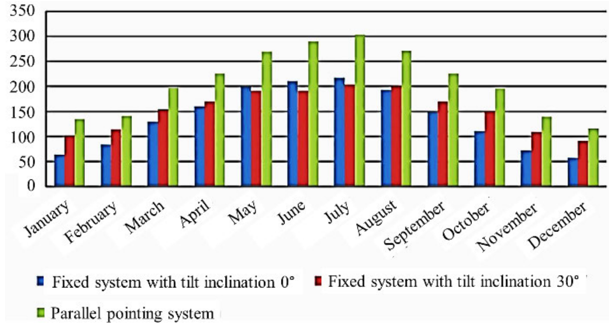


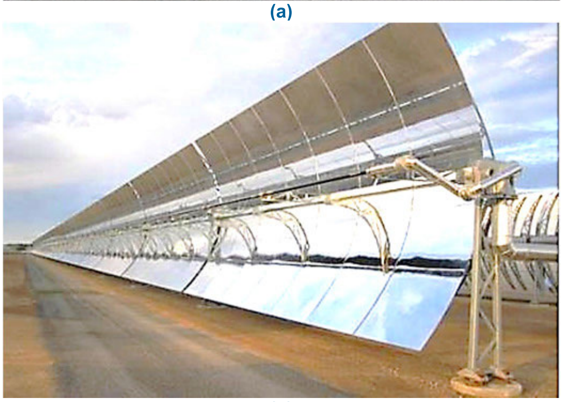
FIGURE 15. Monthly output energy (in kWh) of a robotics-based solar tracker [135].

profiles in the case of static and moving panels. A significant difference in power generation capability in both cases is evident particularly in off-peak timings of sun.

Robots can offer a cost-effective and efficient solution for solar tracking along two dimensions [128], [134]. A study reported in [135] presents an optimized design of a solar tracking system based on a 2-DOF robot with a parallel mechanism. The constrained optimization procedure avoids singularities and collisions between links/joints to permit large operational workspace. Based on the universal and spherical joints, the mechanism can move within the angle range 0° to 90° in elevation and −90° to 90° in azimuth. Figure 15 presents the experimental results in the form of monthly energy assessment compared to fixed solar panels with tilt inclinations of 0° and 30°. An overall improvement of 17.2% in energy production is reported using the proposed robotic system compared to the solar panel placed at a fixed inclination of 30°. Another automated tracking system centered on a mobile robot (QBotix) is reported in [136]. With an electricity consumption of as low as 30 cents/day, the robot is claimed to have an average ability to adjust five solar panels/min. This idea can be extended to multiple mobile robots, which can also function in a coordinated manner for solar tracking of various arrays [137]. Other studies reporting solar tracking systems include [138]–[140].

Furthermore, inspection and maintenance activities of solar plants are also being rendered by robotized systems. MAINBOT [141] is one such platform designed for large industrial plants. The objective was to develop ground robotic vehicles and climbing robots with diversified sensory and manipulation capabilities to navigate in plants following horizontal and vertical paths respectively. The prototype of the robot (shown in Fig. 16a) has been successfully demonstrated on a cylindrical-parabolic collector type solar plant (Fig. 16b) and central tower plant (Fig. 16c). Results of leakage detection and prevention are reported in [142]. As an alternative to climbing robots, recently Unmanned Aerial Vehicles (UAVs) [143], [144] are being used for inspection of solar plants. One such advancement is reported in [145], [146], where a UAV and a thermographic sensor are used for inspection of a Concentrated Solar Power (CSP). Field trials were performed at an altitude of 20, 40, 60, 80, 100 and 120 m above ground

(a)



(b)

(c)

FIGURE 16. MAINBOT [147] (a) Prototype with mock-up (b) Parabolic solar plant used for validation (c) Tower-type plant.

level with cruising speeds of 5, 7 and 10 m/s. Experimental results proved the feasibility of using UAV to perform real-time inspections for detecting anomalous absorber tunes. Table 4 presents the results in the form of the percentage improvement in UAV deployment compared to the manual inspection. Depending upon the altitude and cruising speed, the improvement range in inspection time using a UAV is reported from 85.6% to 98.0%.

IV. ROBOTS IN WIND ENERGY SECTOR

Wind is another superfluous resource that has been professed and explored to produce alternate energy [148].

TABLE 4. %Age Improvement in inspection time of CSPs using a UAV [146].

Altitude (m)	5 m/s (%)	7 m/s (%)	10 m/s (%)
20	85.6	89.7	92.8
40	85.6	89.7	92.8
60	92.5	94.7	96.3
80	92.5	94.7	96.3
100	95.0	96.4	97.5
120	96.1	97.2	98.0

FIGURE 17. Robots painting wind turbines [165].

Wind power can be titled as one of the ancient companions of human civilization, like solar power [149]. A wind turbine converts the kinetic energy of the wind into mechanical power [150]. The resulting mechanical power can either be used directly or can be converted into electricity as per requirements. A typical turbine consists of a generator, main bearing, a rotor, a gearbox and shafts corresponding to low-speed and high-speed [151]. A housing called nacelle houses all these components. This technology has now been advanced to a reliable level of sustainable electricity generation source [152]. However, the cost of the technology is a point of concern [153] though technological advancements have substantially reduced the constructional as well as operational costs of wind turbines [154]. The key objective of turbine control is to optimize the extracted power. Techniques for turbine control include; blade angle adjustment, turbine rotation adjustment and speed control. Studies investigating the control of wind energy systems are reported in [155]–[157], while control of wind turbines has been reviewed in [158]–[160].

Multi-DOF robotic manipulators with large link lengths are well-suited to handle wind turbines and towers. Robots deployment has addressed various manufacturing challenges by devising joining and cutting technologies and has offered lower-cost production of wind tower equipment [161]. Intelligent robotic tools meet the drilling requirements of surfaces of the nacelle. Based on vision and force control laws, robots ensure accurate drilling, mating and alignment. Also, robots safeguard against inadequacies on surfaces of blade turbines by assuring adequate surface preparation and thus can assist in sanding applications. Moreover, robots are being used for painting towers and nacelles of wind turbines (Fig. 17).

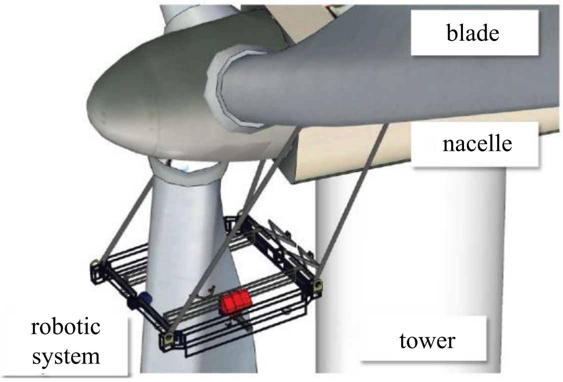


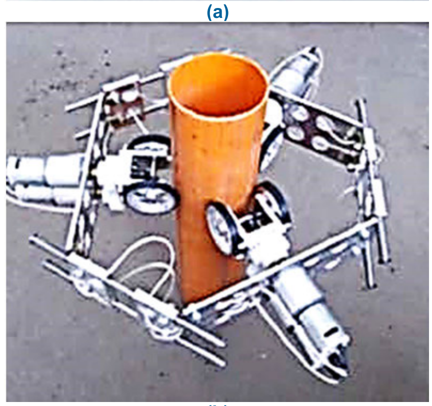
FIGURE 18. Conceptual model of a wire-driven robot working in an offshore wind turbine [166].

Wind farm productivity, reliability and performance depend on monitoring, inspection and fault diagnosis of the turbines [162], [163]. Inspection detects damage due to bounding defects, air inclusions, delamination and lightning strikes and cracks. Inspection of blades of a wind turbine using traditional methods is a time consuming and dangerous task [164]. As in the solar PV sector, robots are also being used for inspection, monitoring and O&M of the turbines. Figure 18 presents a simplified conceptual model of a wire-driven robotic system intended for O&M of an offshore wind turbine.

General Electric presented a track-based remote-controlled robot (Fig. 19a) that can climb 300 feet [167]. Using an onboard vacuum pump, the robot sticks to the wall of a wind turbine by removing the air between the machine and the turbine. The sensory system consists of an on-board camera for visual inspection of blades. Another robot [168] for monitoring the structural integrity of the insides of blades has been proposed by researchers at London South Bank University (LSBU). The blade inspection is based on axial X-ray tomography with a scanner whose X-sectional dimensions must be 1mx2m to envelop the blade completely. As a concept demonstrator, a small scaled prototype of the robot (Fig. 19b) has been developed that can perform three types of climbing motion patterns; up/down, spiraling and rotation about the circumference. Fraunhofer Institute for Factory Operation and Automation, Germany developed a novel wire-drive robot (Fig. 19c) for inspection of onshore and offshore turbines of any size [169]. The project, named as RIWEA, was intended to design an autonomous robot that uses four ropes to move up and down. The robot uses infrared radiator and ultrasonic sensor, thermographs and images acquired from a high-resolution camera for inspection of bonded spar joints, leading edges and trailing edges.

Inspection using aerial vehicles is also getting attention in the scientific community [170]–[172]. Due to their high mobility and diversified sensing capability, the aerial vehicles can inspect the structures faster. Figure 20 shows a conceptual design of a micro aerial vehicle type wall-climbing robot. A two-phase approach given in Figure 21 can be realized to achieve precision in the inspection task while still ensuring high speed. At first, 'macro inspection' is performed to find an approximate damaged area using a thermographic camera mounted on an aerial vehicle flying in the vicinity of the

(a)



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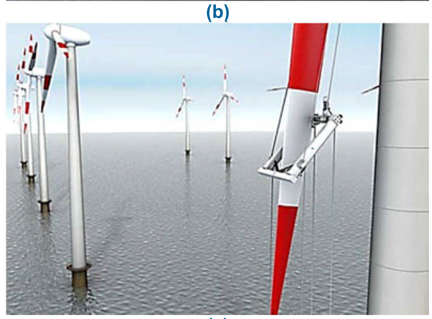

(c)

FIGURE 19. Climbing robots for inspection of wind turbines: (a) GE robot [165] (b) LSBU robot with mockup [168] (c) RIWEA project [167].

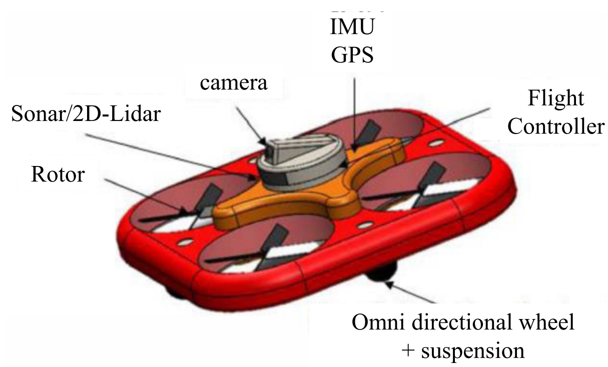

FIGURE 20. Conceptual design of a micro aerial vehicle type wall climbing robot [172].

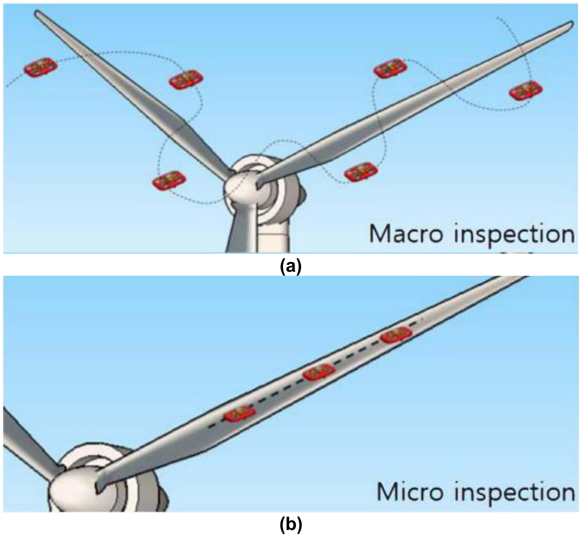

FIGURE 21. Levels of inspection for wind turbines [172]: (a) Macro inspection (b) Micro inspection.

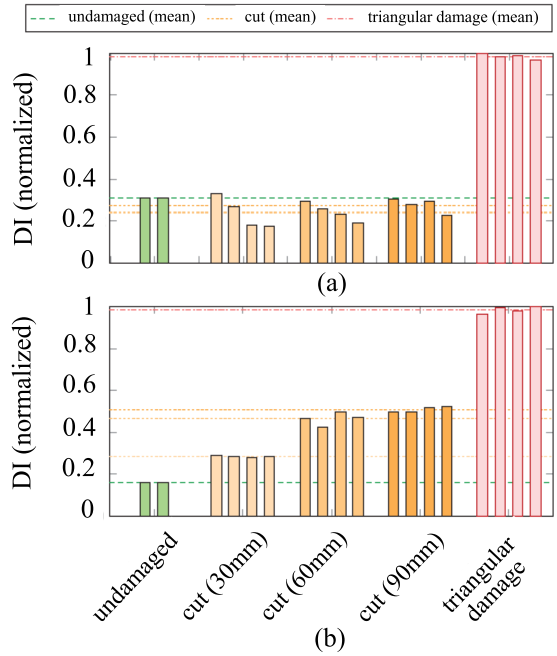

FIGURE 23. Experimental results of damage detection in blade-tip sample at [174]: (a) 24 GHz (b) 35 GHz.

blades of the turbine. This area is then thoroughly explored in the second phase of 'micro inspection' for precise localization of the damage location.

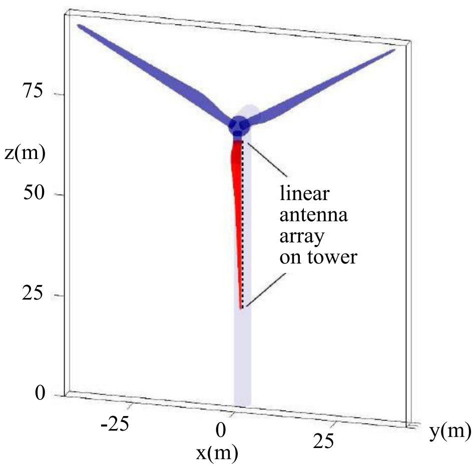

FIGURE 22. Arrangement of antennas for radar-based inspection [177].

Another emerging concept for continuous structural health monitoring of wind turbines relies on millimeter-wave and terahertz technology and employs radar technology [173]–[176]. The central idea is to place both the transmitter (TX) and receiver (RX) antennas on the tower and then using the TX antenna to radiate waves towards the blades of the rotor. The automated and non-contact inspection of the blades is based on the principle of inverse synthetic aperture radar exploiting the rotational motion of the turbine. All blades can be inspected in this way by mounting an array of sensors. Figure 22 shows a typical arrangement for a radar-based inspection strategy. Experimental results for damage detection at two different frequency bands are illustrated in Fig. 23. It is concluded that damage quantification is better done at the 35 GHz band.

Going beyond inspection, Japanese researchers developed a novel robot for the repair of the leading edge of the blades [178]. The novelty of the robot lies in its smaller size and ease in control to perform contact work. The vertical motion is realized using an on-board winch system that considers blade as a rail. A rope can also be used for landing/take-off of the robot-assisted by an operator on the ground. Images acquired from an on-board camera are viewed using smart glasses worn by the operators. Experimental trials demonstrated that the proposed system (Fig. 24) can reasonably move on the blade of the wind turbine. Other notable research works highlighting the instrumental role of robots for O&M of wind turbines include [166], [179]–[181].

The blades of wind turbines get contaminated over time due to dust, ice, oil, marine salt, mosquitoes, flying plankton, etc. Experimental studies investigating the performance deterioration due to contaminations on the blade surfaces are reported in [182]–[185]. Figure 25 shows a typical power curve for a 300kW wind turbine. It is evident that the contamination significantly affects the power generation capability of the turbine particularly after three months.

Cleaning approaches can be broadly categorized into manual, semi-automatic, or robotic-based autonomous solutions. Table 5 presents a comparative summary of these approaches. Manual cleaning of blades involves at least three human personnel and takes about four hours for cleaning each blade, thereby necessitating wind turbines to keep on halt during cleaning operation [186]. Also, manual procedures can only

TABLE 5. Comparison of various approaches for cleaning of wind turbines blades [187].

Specifications	Manual	Semi-automatic	Robotic-based
Cleaning time (per turbine)	4 X 3 hours	1.5 X 3 hours	½ - ¾ hour
Labor intensive	High	Moderate	Low or None
Water consumption	High	Moderate	Low or None
Operational condition	Stopped	Stopped	Running
Safety	Unsafe for blade and laborers	Safe	Safe
Economic viability	Uneconomical	Uneconomical	Economical

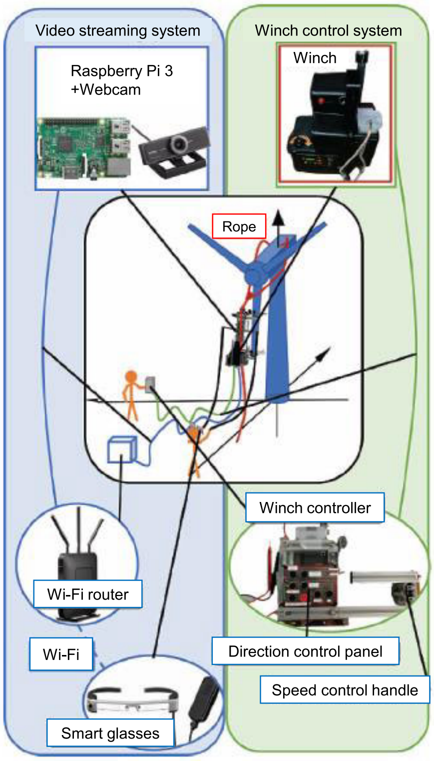

FIGURE 24. System overview of a robot for inspection and repairing blades of a wind turbine [178].

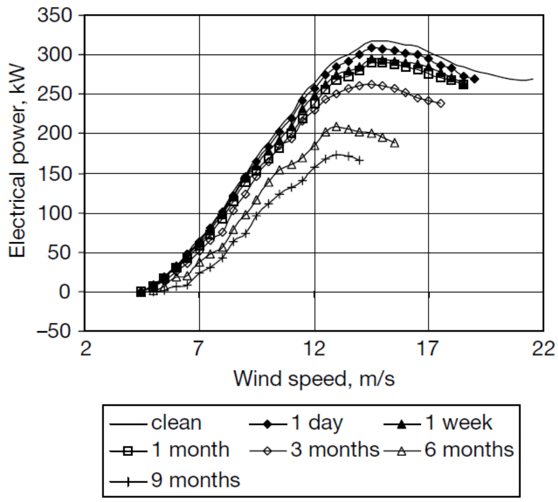

FIGURE 25. Effect of dust on the power curve of a typical wind turbine [182].

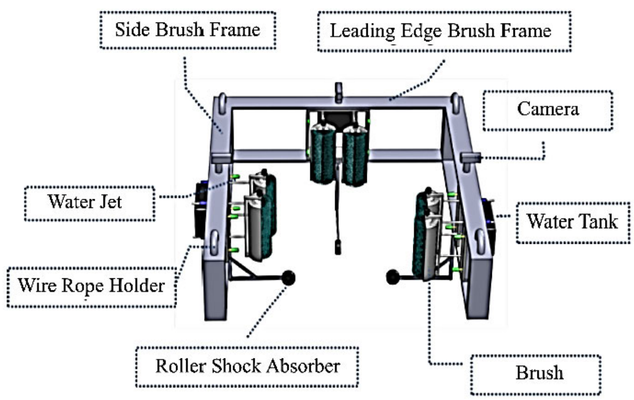

FIGURE 26. Blade cleaning robot [187].

be conducted only in the absence of blowing wind. An alternate solution [187] has been proposed by installing a water hose on the pillar and then spraying water with the detergent. This method also suffers from limitations since it requires a pump to uplift water. Robotic vehicles with an ability to climb have the potential to offer an optimal solution to clean the blades by saving time, cost and efforts while ensuring safety. Figure 26 illustrates one such autonomous robot [187] equipped with a water jet and brush for cleaning. Water in the tank is limited to 350 liters. The control system is centered on a Programmable logic controller which synchronizes three other microcontrollers.

Table 6 summarizes the role of robotics in wind farms. It is evident that manufacturers of wind energy systems incorporate robotic-based automated solutions in both the fabrication and operation phases.

In contrast to energy generation using conventional tower mechanism, the last decade witnessed a rapidly evolving class of airborne energy systems to capture high altitude wind power [188]. Figure 27 illustrates the various types of aircraft/kite used for energy generation. The most common way of generating airborne wind energy is based on power kites. The kites are tethered aerodynamic devices that can be automatically controlled for launching, maneuvering and landing using robotics and automation technology. The factors that need to be considered while designing a power kite include; line length, wingspan, robustness, efficiency, stability and manufacturability. The moving light-weight structure consists of airfoils and lines. The operational principle of a pumping kite system consists of two main phases; initially,

TABLE 6. Applications of robotics in wind energy sector.

Phase	Functional description of robot	Reference works
Fabrication	• Blade manufacturing • Drilling on the surfaces of nacelle of wind turbines • Mating and alignment	[259-262]
	• Assembling wind turbines	[161]
	• Sanding	[263, 264]
	• Painting towers and nacelles	[165]
	• Automation of material flows and storage	[265]
	• Installation of vortex generators • Installation of leading-edge protection tape • Applying blade coatings	[219]
Operation	• Monitoring and inspection of turbines • Diagnosing fault	[162-164, 167-169, 173] [170-172, 174-176, 266]
	• Maintenance of turbines	[166, 178-181]
	• Removing contaminations on blades (cleaning)	[186, 187, 267]

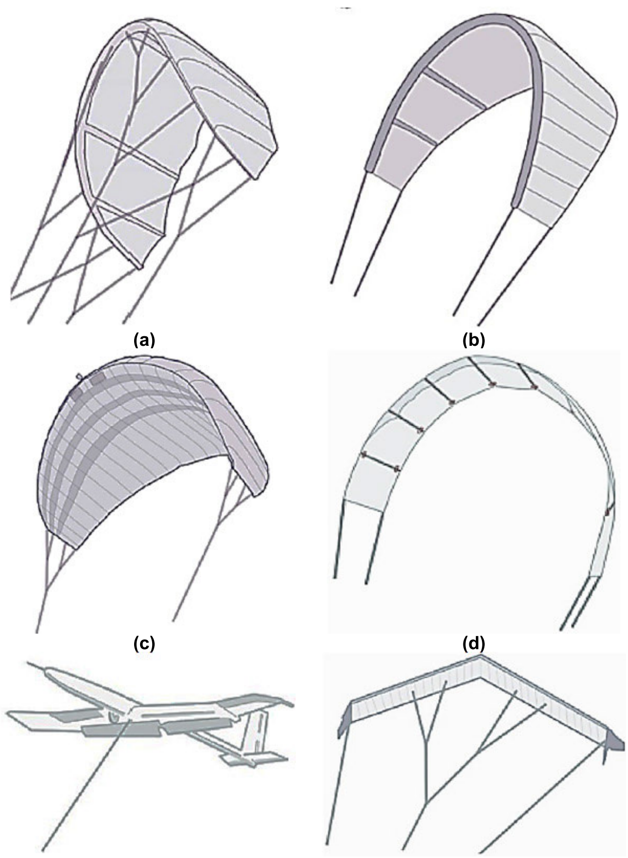

FIGURE 27. Various types of kites/aircrafts for airborne energy systems [199]: (a) LEI SLE (Leading Edge Inflatable, Supported Leading Edge) Kite (b) LEI C-Kite (c) Foil Kite, design from Skysails (d) Semi-rigid wing (e) Glider, design from Ampix Power (f) Swept rigid wing, design from Enerkite.

the kite is reeled out while it is moving high upward in cross-wind direction following a similar trajectory as number '8'. The lines transfer mechanical power to the heavy on-ground equipment where this power is converted into electrical power. The second phase consists of depowering the kite, steering it to zenith and reeling in.

Table 7 presents a comparison of power generation using traditional wind towers and power kites. It is highlighted that meaningful use of kites depends on its control and automatic adoption to changing wind conditions. Various nonlinear and optimal control laws have been proposed by the scientific community for winch control and flight-path control to ensure stable operations of power kites. A nonlinear MPC to maximize the energy obtained by the kite is reported in [189] with an implementation of the control law based on approximation of set membership function. The derived kite generator model considers gravitational forces, apparent forces and kite aerodynamic forces. Experimental results consisting of measured generated power and length and speed of line demonstrated successful capturing of wind energy up to 500-700m.

Optimal control techniques proposed for non-linear systems having state constraints can find potential in control of powered kites. One of such techniques is reported in [190], which proposed an adaptive time-mesh algorithm based on refinement criteria. The criteria use the information of the adjoint multipliers and involve multi-level refinement unlike earlier works [191], [192] and validates the results by applying the Maximum Principle of Pontryagin.

For more details, interested readers are referred to studies reported on modeling [193], control [194], optimization [195], path planning [196], economic analysis [197] and technologies [198] associated with airborne systems.

V. ROBOTS IN OTHER RENEWABLE ENERGY SECTORS

Recently, the robotics has broadened its application horizon beyond solar and wind sectors. The present decade witnessed robots in other forms of energy driven by water and biological resources.

A. HYDRO ENERGY

In hydro energy, the robots are used in the fabrication and refurbishment of hydro equipment without having to dismantle them. They reinforce hydroelectric turbines and enhance

TABLE 7. Wind energy generation - comparison between wind tower and power kites (✓ indicates relatively better compared to X).

Parameter	Wind Tower	Power Kite	Remark(s)
Construction cost	X	✓	‣ Heavy structure of kites reside on the ground while the moving parts are light-weight thus making the airborne system economical
Infrastructure requirements	X	✓	‣ Wind tower requires heavy foundations and huge blades
Operational constraints	X	✓	‣ Wind tower can operate at a max. height of about 150m and can generate energy at locations with wind speeds at 50-150m of height w.r.t ground ‣ Kites can typically fly up to 1000m where constant and strong wind is available
System safety	X	✓	‣ Compared to power kite, damages in wind tower have more serious consequences physically as well as economically
Power density	X	✓	‣ Power grows with the cube of wind speed. Essentially, power kites over-performs than wind tower
Easiness in control	✓	X	‣ Power kite needs sophisticated automatic controls due to input and state constraints and operational environment. Flexibility in the tether and inherent instability call for a robust control law
Reliability	✓	X	‣ Power kites are less reliable due to their intrinsic nature.

their performance by increasing operational efficiency [200]. The dimensions of wickets used in hydroelectric turbines range from 10-15 feet in length, 3 feet in width and 6-10 inches in thickness. So, manual welding is not a feasible option due to large dimensions. Manual welding may result in voids and thus lead to structural problems since wickets are subjected to high stress. Also, welding of wickets demands their rotation to access every part thus making flexible robots an ideal choice for welding.

A recent example of robot deployment in innovative welding processes is demonstrated by the 'Genesis System' – a US-based company, which uses robots to weld wicket gates of hydroelectric plants. The robots effectively helped to improve the speed, quality and accuracy compared with the performance achieved through manual procedures. Researchers from Quebec Canada, presented a novel track-based multi-process robot named SCOMPI [201]. It is a 6-axis portable robot that has been specifically developed for hydro equipment like headgates, turbines, penstocks and spillway gates. The design of the manipulator is based on operational constraints imposed by a curve surface within a confined space. A new measurement system provides a high-resolution 3D scan of the track. The robot has been rigorously tested for diversified applications in hydropower production, including welding penstocks, repairing turbine runners and refurbishing tracks of head-gates. Figure 28 (a-b) illustrates the applied use of SCOMPI. A typical response in the form of the robot's most flexible mode during grinding operation is shown in Figure 29a [202]. Grinding was performed with 6000 rpm on 30cmX30cm plates. Careful observation revealed the presence of vibro-impact behavior in the response with a transient frequency of 800 Hz. In another test of cutting a plate with overlap traverse grinding, Figure 29b [203] shows a depth profile as acquired from Altisurf 530 profilometer. Various successful demonstrations of SCOMPI over the last two decades resulted in its extensive deployment in diversified applications in the hydropower sector.

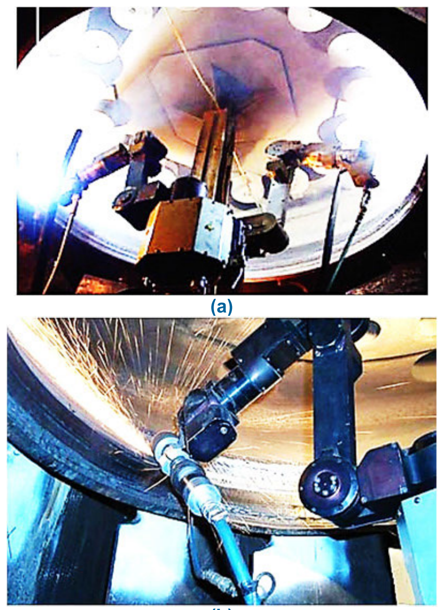
(a)
(b)

FIGURE 28. SCOMPI in operation [201]: (a) On-site installation. (b) Peening and grinding.

Robotic crawlers are now being employed in hydropower dams and wind turbine foundations to inspect concrete structures. Electric Power Research Institute (EPRI) designed and developed one such crawler (Fig. 30a) with on-board Simultaneous Localization And Mapping (SLAM) and advanced non-destructive evaluation instrumentation developed for long term operational support of renewable, nuclear and fossil

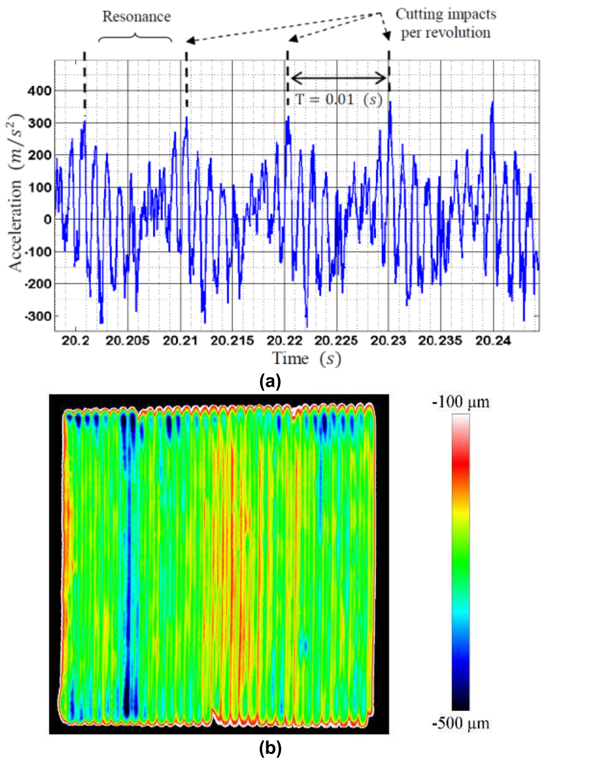

FIGURE 29. **SCOMPI in operation: (a) Vibration profile along the robot's most flexible mode during grinding [202] (b) Depth of cut profile after surface grinding [203].**

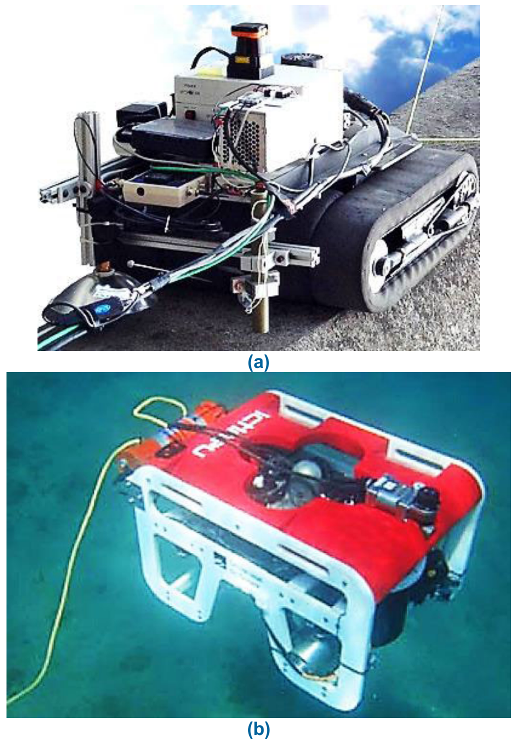

FIGURE 30. **Robotic crawler for inspection of structures: (a) EPRI's robot [204] (b) Univ. of Girona's AUV [205].**

generating resources [204]. Another robotic rover (Fig. 30b) for exploring the walls of hydroelectric dams has been presented by researchers from the University of Girona, Spain [205]. The Autonomous Underwater Vehicle (AUV) can be controlled in 4-DOF, i.e. sway, surge, yaw and heave. It can visually inspect the dams based on intelligent control architecture, sensory data from buoy and image processing techniques.

B. BIOLOGICAL ENERGY

This form of renewable energy is obtained from living organisms like plants, wood or gases extracted by micro-organisms. The sources for this alternate energy can be categorized into biomass and biofuel. Due to direct acquisition and storage of energy in the plants without employing any manufacturing technology, bioenergy offers more reliability compared to solar or wind counterparts. Given the abundance of organic waste, paper, household garbage, etc., bioenergy has the potential to supply energy indefinitely. Scientific community from robotics and renewable energy has been exploring the ways to advance applied research in biological process control, bioengineering, robotics and bio-sensing. Notable avenues of research include [206];

- Applied robotics molecular biology platform
- Floating robotics algae farms
- Virtual production approaches in forestry.

The core idea behind applied robotics platforms in areas like Structural biology or Vaccinology is to automate the protocols in gene cloning and expression processes to improve microbial strains for producing biofuel. These intelligent platforms improve operational scalability, procedural consistency and processes throughput. Robotic-based solutions also offer traceability of samples, reproducibility of results and ease in data acquisition and storage [207]. It is demonstrated in [208] that semi-automated solutions can provide 93.6% higher cloning success rates compared with the manual procedure. A novel biological robot for improving the throughput of colony picking is presented in [209]. The novelty of the proposed system lies in its structure (composed of a multi-pin synchronous manipulator) and its ability to simultaneously pick, inoculate, clean and heat. The estimated throughput rate of the system is 2400 colonies/hour. Figure 31 illustrates the structure of the visual servo system for the robot. Another multi-purpose integrated robotic solution for the bioenergy sector is reported in [210], which can produce complementary DeoxyriboNucleic Acid (DNA) libraries, pick colony, isolate plasmid DNA, transform yeast and bacteria, express protein and perform suitable functional assays. These operations can tailor microbial strains to use renewable feedstock to produce fertilizers, bio-derived chemicals, biofuels and other products for bio-refineries.

A self-sustainable floating robotic algae farm can turn algae sludge into biofuel [211]. An example of floating algae is a tub-sized algal biofuel farm innovated by 'BEAR Oceanics' [212]. The robot floats in remote-controlled areas of the ocean without colliding with boats and ships using its vision ability. Powered solely with solar and wind resources,

TABLE 8. Typical types of robots in renewable energy sector.

Sector	Application	Robot's type Manipulator-type	Mobile robot
Solar	• Cell and wafer handling	√	
	• Installation and construction of panels	√	
	• Assembling and transportation of panels	√	√
	• Packaging and palletizing	√	
	• Cleaning of panels		√
	• Solar tracker		√
	• Inspection and maintenance	√	√
Wind	• Painting of turbine blades	√	
	• Inspection of turbines		√
	• Assistance in large scale production	√	√
	• Drilling holes in turbines	√	
	• Cleaning of blades		√
Hydro	• Installation	√	
	• Peening and grinding	√	
	• Polishing blades	√	
	• Inspection of structures	√	√
Bio	• Floating robotics algae farms		√

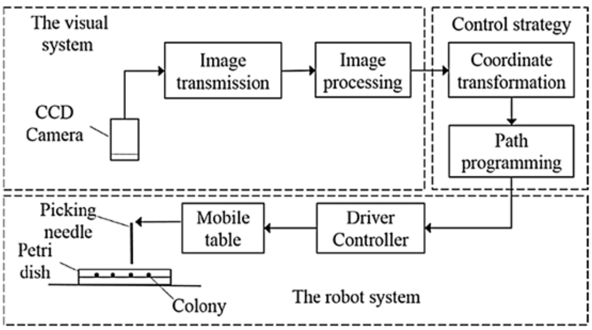

FIGURE 31. Structure of visual servo system for colony picking robot [209].

FIGURE 32. Ocean robot farming fuel from algae [212].

the farm has biofuel production ability of 5 gallons per day without using any chemical or resulting in toxic waste. The biomass is converted into biodiesel by bursting cells of algae with a small electric current and using thermal depolymerization phenomena. Figure 32 shows the robot farm developed as a technology demonstrator on a small scale. However, the idea can be envisaged in the future to have spawn fleets of robotic farms that can generate biodiesel for fueling vehicles, trains and aircrafts simply by harnessing ocean winds and solar energy.

Virtual production approaches can play an instrumental role in sustainable forestry to fulfill the demands of bioenergy in the near future [213]. These production approaches are already well-established in mechanical and industrial engineering. A recent trend is to extend this idea in forestry [206]. Simulation helps in choosing an optimal approach by estimating and comparing costs involved in various approaches. Also, the virtual rendering in a graphical environment permits a user-friendly interpretation of the simulation results. As a preliminary step, a 'forest machine simulator' has been recently realized, which involved the integration of knowledge from robotics and geo-informatics by generating virtual forests online using topographical data.

Table 8 briefly outlines the types of robots in various renewable energy sectors. In general, manipulator-type robots are used for painting, assembling, welding, transporting and accomplishing other common tasks in numerous application scenarios. Table 9 summarizes prominent manipulator-type robots with their key specifications that find potential in the energy sector.

VI. CHALLENGES AND OPPORTUNITIES OF ROBOTICS IN RENEWABLE ENERGY SECTOR

Renewable energy is now considered as an established source to meet global energy demands in the face of increasing gas and petroleum prices. The present decade witnessed increasing trends of robot deployment in renewable energy setups leading to enhancement in the system's performance with reduced costs.

The major presence of robotics in this sector is in solar and wind energy systems. Although highly reliable, the solar generation outlays significantly added expenses.

TABLE 9. Prominent manipulator-type industrial robots (arranged alphabetically).

Company	Model	Weight (Kg)	DOF	Max. reach (m)	Payload (Kg)
ABB	IRB-580	630	6-7	2.18/2.56	10
	IRB-7600	2550	6	2.55-3.50	150-500
Adept	Adept Viper	28	6	0.653-1.298	2.5-5
Comau	Smart5 NJ4	1080-2005	6	3.002	270
FANUC	S-12	230	6	1.605	12
Kawasaki	KG-264	795	6	2.67	12
KUKA	KR 40 PA	700	4	2.091	40
	KR 180 R3200 PA	1093	5	3.195	180
	KR 300-2 PA	2150	5	3.150	300
	KR 700 PA	2850	4	3.320	700
	KR 2000 Series	1300	6	2.7-3.1	150-210
Miller/Panasonic	TA 1900	185	6	1.895	6
Motoman	EPH Series	1445-3050	6	2.651- 3.505 (H) 2.629 - 4.151 (V)	100-200
	MPK Series	60-670	4-5	0.9-1.893 (H) 1.668 (V)	2-50
	MPL series	550-2550	4-5	2.061-3.159	80-800
	MPL80	550	5	2.061 (H), 3.291 (V)	80
	MPP3	115	4	1.3	3
	Yaskawa SDA10D	220	15	1.97 (H), 1.44 (V)	10/arm

The cost and efforts to produce electricity from sunlight are considerably high though the price is decreasing by employing recent developments in modern semiconductor materials [214]. First-rate handling is a prerequisite, right from the production phase of these wafers to the solar panel installation and maintenance [215]. Wind energy is another form of clean energy which is vastly practical in areas having a wind speed of 10mph. The industry gets to benefit from robots in construction as well as in the finishing of turbines. Robots can help in addressing the constraints which impede the use of wind resources to their full potential. Both solar and wind installations are more likely to be carried out in remote areas possibly involving toxic elements. Besides, solar and wind plants are mostly set up in large fields incorporating the large quantities of panels and blades where installation, operation and maintenance of these modules and the associated structure remain a challenge. In such circumstances, robots are perfect candidates to execute safe and automated conduct with high precision and productivity from locating parts to maintaining renewable resources.

Following are the challenges and opportunities that may serve as guidelines for future directions of R&D in the cross-section of robotics and renewable energy:

- The primary challenge of robot deployment in renewable energy setups is the immense need to reduce costs per watt and to meet requirements of the demand-supply chain. Due to the high relative cost of PV modules and wind turbines in comparison with conventional energy resources, the economic value of renewablesources is recognized over several years. Although the cost of producing energy with renewable resources is dropping off due to technological advancements, researchers and industrialists strongly feel that the price per watt cannot yet compete without explicit incentives due to being far from optima. Incorporating robotics-based automation in these setups may address this limitation by offering prominent features like high volume, high yield, a quick change in specifications, adaptability and thorough inspection throughout the product life cycle. Considering the economics aspect [216], the scientific community needs to put new investment in mechatronics and renewable energy technologies to guarantee a suitable balance in achieving clean energy milestones, ensuring energy security and expediting economic progress.
- Regular inspection of renewables is extremely important for cost-effectiveness. Failure to detect a minor problem in a $1,000 bearing may lead to total repair costs of $200,000 for a multi-MW wind turbine [217]. Deployment of robots in various sectors of renewables is a recent trend; therefore, in terms of its cost-effectiveness, not much quantitative data is available from the already deployed systems. In a new fully autonomous offshore wind farm O&M project, named MIMRee (Multi-Platform Inspection, Maintenance and Repair in Extreme Environments), the expected cost saving is around £26 million throughout farm lifetime [218]. Full autonomy is planned to be achieved through autonomous vessels, crawling robots and aerial vehicles. This is a significant cost saving in one project since the global loss due to inefficient blades of the turbine is reported to be over $4 billion per year [219]. Another study evaluating the cost-benefits of remote inspection of offshore wind farms is reported in [220]. The scenario consisted of an offshore wind farm of 100 wind turbines, each of which has 3MW rated power at the cost of €2400 per KW. The farm is remotely located at a distance of 40km from a harbor. The estimated cost of a condition monitoring system is €160,000. An additional €80,000 is associated with the

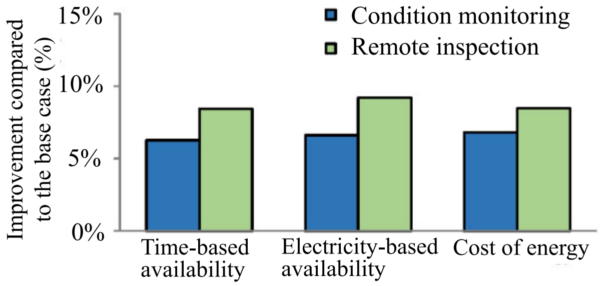

FIGURE 33. Cost-benefits evaluation of inspection of an offshore wind farm [220].

remote inspection system. Simulation results (Fig. 33) dictate over-performance of remote inspection both in terms of energy cost and availability. These comparative results are %age improvement with reference to a base case.

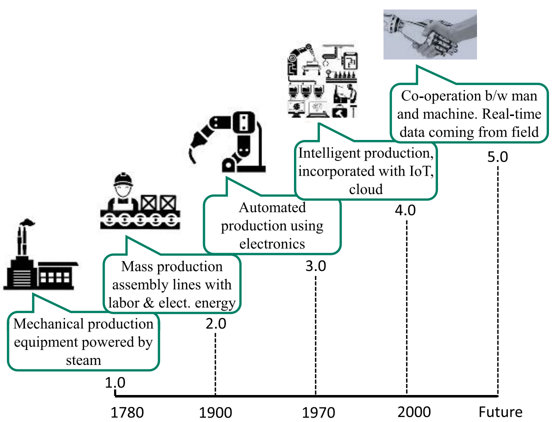

FIGURE 34. The domains of robotics and automation are reshaping various industrial processes in the context of industrial revolutions.

- Thanks to technological advancements, we are now witnessing Industry 4.0 (see Fig. 34), where autonomous robots are playing the key role owing to their autonomy, intelligence and power [221]. The growing concept of Industry 4.0, particularly in the context of 'smart factory' [222], 'smart energy' [223] and 'smart grids' [224] is primarily due to advancements in digital technologies of which robotics and IoT are instrumental drivers. The role of the digital industry in the renewable energy sector from the perspective of the fourth industrial revolution is recently reported in [225]. It is concluded that digitized industries have the potential to increase energy efficiency, to provide flexibility for renewable energy systems and finally to enhance transparency on the status of the energy system.
- The futuristic way of getting things done in the renewable energy sector is anticipated to be eight times faster reducing the labor workforce by 1/10. This challenge, e.g. implies that 80x more PV panels can be installed by the same number of laborers compared to manual operation, thus demonstrating an exceptional increase in productivity.
- Most (if not all) of the robotic manipulators found in the renewable sector are based on rigid links, which are usually made up of Aluminum or Iron [226]. In contrast, robotic systems with flexible links and/or joints offer lightweight, reduced inertia, low manufacturing cost and permit faster movements [227], [228]. The applications of these flexible robotic manipulators [229], [230], which are made up of lightweight carbon fiber, stainless steel or light Aluminum, need to be explored in the renewable energy sector.
- Much of the research on control of systems reported in the last decade has been based on linear control laws [231]. In contrast, nonlinear control systems offer more precision and exhibit better performance especially in the environments polluted with external disturbances, as discussed in [232]. A recent trend is to apply modern control laws in the renewable sector. This trend needs to be continued in the future.
- Mobile robots are also used in renewable setups for tasks involving mobility. The latest avenues of research in mobile robots address their operational performance with constraints that need to be explored in the renewable energy context. Examples of these avenues include; navigation [233]–[235], path planning [236], collision detection [237], [238], slip avoidance [239], [240] etc.
- Most of the reported works presenting deployment of robots in renewable sectors involve a single robot accomplishing the required task. Multiple homogeneous or heterogeneous robots can coordinate among one another for the execution of a task, e.g. panel cleaning, painting, welding, etc. Thus, Swarm-based robotics [241] can be explored in the renewable sector for enhancing productivity and quality at a reduced timeframe.
- Both solar and wind energy systems require a battery to absorb part of the generated energy for later utilization. Owing to hazardous elements in battery, intelligent robots can also find potential in battery manufacturing [242].
- The long-term sustainability and viability of robots in the renewable sector are strongly linked with their autonomous and optimal operation backed by accurate forecasting techniques. Consequently, various concepts from computer science like artificial intelligence [243], [244], neural networks [245], machine learning [246], fuzzy logic [247], etc. find enormous potential that needs to be unleashed from the renewable energy perspective.
- In developing countries like KSA, which are enriched with renewable resources, industrialists and business people need to be educated by realizing them robotics potential in renewable energy setups and convincing them to replace traditional manufacturing, installation and maintenance methods by robotics-based solutions.

TABLE 10. [268] Amount of energy produced in saudi arabia based on type of production (MW).

Year	Steam Generators	Gas Generators	Combined Cycle	Diesel Generators	Solar	Others	Total
2014	16,782	24,527	6,899	1,911	0.5	15,386	65,506
2015	16,782	24,282	8,708	1,543	0.5	17,839	69,155
2016	19,350	22,980	11,954	1,434	0.5	18,983	74,702
2017	21,988	20,953	13,379	989	0.5	23,161	80,471

This will help to globally uplift advancements in the integration of robotics and renewable energy.

VII. BRIEF CASE STUDY

The potential of robotics in the renewable energy sector is presented with a case study of Saudi Arabia. Vision 2030 of the Kingdom has three major goals; a vibrant society, an ambitious nation and a thriving economy. The Saudi government has recognized the crucial nature of diversification of the energy sources for long term economic prosperity. One of the major strategic initiatives in Vision 2030 is the National Renewable Energy Program (NREP), which is managed by the Ministry of Energy. The geographical location of the Kingdom renders the overall effect of the environmental factor to be positive in terms of the efficiency of harnessing the sunlight energy as well as wind energy [248].

The total energy produced in Saudi Arabia has reached more than 80 GW, the vast majority of which is from fossil fuels and crude oil production processes. Table 10 presents the breakdown of the energy sources from 2014 to 2017. This situation is not sustainable, neither economically nor environmentally. To deal with this situation, the NREP aims to gradually boost the renewable energy share in the total mix of energy sources [249]. By 2030, the solar power based on PV is targeted to be 40 GW [250] and the wind power production target is set at 16 GW [251]. Figure 35 presents a chart showing short term and long-term targets. By 2030, renewable energy is going to constitute more than 50% of the current total production (i.e., 56 GW clean energy in 2030 compared to 80 GW total energy in 2017). Such a distribution indicates the government's preference for the renewable energy. A quantitative research study reported in [252] reveals significant willingness among the people of the Kingdom to adopt technologies related with renewable energy primarily due to the economic factor.

The kingdom is determined to reach its targets, which may be challenging. The successful development and utilization of renewable energy projects depend on many vital factors, including economics, industrial, environmental and social, as well as law and policy factors. The first two factors call for the need of technological support such as robotics and automation.

KSA has timely realized the pivotal role of robotics technology in achieving Vision 2030 [254]. The announcements of megaprojects like Neom ($500 billion city of robots and renewables) and preparations to launch a joint initiative with Japan's SoftBank are the two recent examples that truly reflect the Kingdom's realization to use robotics for prosperity and sound growth in several pertinent areas. It is interesting to mention here that in Oct. 2017, Sophia (a humanoid robot!) was granted Saudi citizenship.

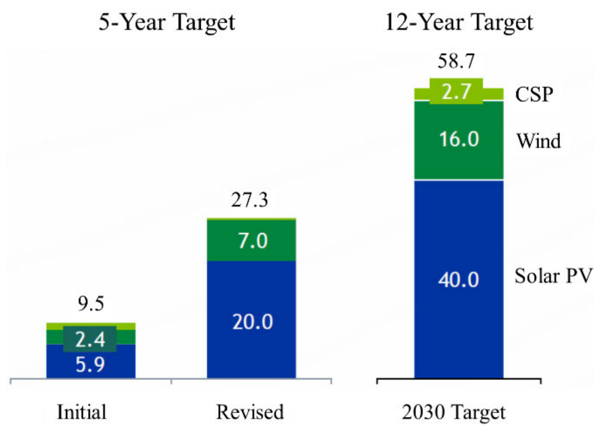

FIGURE 35. Planned capacity (in GW) indicating an increase in renewable energy targets by 2023 and 2030 [253].

In an attempt to develop the robotics culture in the country, IEEE (Saudi Arabia section) and Arab Robotics Association joined hands to hold the Kingdom's leading annual event on robotics "*Saudi Robotics Conference & Expo*" organized annually in Jubail Industrial City [255]. The event offers a full spectrum of showcasing cutting edge technologies and state-of-the-art solutions involving robotics and automation in various traditional industrial applications. In particular, four categories are addressed: Smart manufacturing, industrial robots, operational safety and skills for future technology.

Given the enormous potential of renewable energy in the country and recently realized the importance of robotics, huge potential and opportunities of robotics and automation exist in the Kingdom in various applied spheres including the renewable energy sector. The government intends to unleash this potential by investing in the energy sector, enriching R&D culture, strengthening industry-academia linkages and developing infrastructure for the renewable energy industry.

VIII. CONCLUSION

This paper comprehensively reviews the integration of robotics in the renewable energy sector. Recent state-of-the-art robotic systems that are already operational or currently under-development in renewable setups are highlighted. Future directions of research and suggestions to further strengthen the integration are also discussed. It is concluded that robots have got the right potential for meeting the requirements of various processes in the renewable sector especially in the manufacturing of products and O&M of setups designed to harness renewable energy sources. The quality control and productivity can be improved by the consistent and precision performance of the robots. Remote inspection robots can be deployed in troubleshooting and even maintenance of the renewable systems. Robotic crawlers with onboard microwave or ultrasonic transmitters, can penetrate in structures for fault identification in materials. Potential in autonomous robots can be unleashed to optimize the supply chain to build wind and solar farms. Self-driving machines can transport components of a solar array or wind turbine from factories. Intelligent and highly precise robots can be deployed for assembling the structures. Thus, from production to assembly of resources, robots with user-friendly software and sophisticated control have got the potential to reduce cost without compromising quality in the global market. It is anticipated that this systematic review will be beneficial for roboticists, technologists, engineers, researchers and industrialists in developing a more rigorous practical understanding of the integration of the current state of robotics in renewable setups.

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