electronics

Review

Quantum Mechatronics

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Abstract: Mechatronics systems, a macroscopic domain, aim at producing highly efficient engineering platforms, with applications in a variety of industries and situations. On the other hand, quantum technologies, a microscopic domain, are emerging as a promising avenue to speed up computations and perform more efficient sensing. Recently, these two fields have started to merge in a novel area: *quantum mechatronics*. In this review article, we describe some developments produced so far in this respect, including early steps into quantum robotics, macroscopic actuators via quantum effects, as well as educational initiatives in quantum mechatronics.

Keywords: mechatronics; quantum technologies; robotics; sensing; actuators; education

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1. Introduction

The purpose of this review is to describe some of the recent literature connecting the fields of mechatronics and quantum technologies. The former is mainly an area of mechanical engineers, while the latter is an area of quantum technologists and scientists. We do not aim at being exhaustive with the literature we describe, but to provide an overview of what, in our view, is recent and useful research productivity that serves to connect both fields. The aim of this review is to motivate both communities to work together toward a common goal of incorporating quantum technologies into mechanical engineering devices, for enhanced communication, computation, and sensing.

1.1. Mechatronics Systems

The field of mechatronics concerns multi-physics systems, which typically have more than one physical domain (for example, domains among mechanical, electrical, fluid and thermal) [1–4]. The "enhanced" mechatronics approach involves the following four characteristics:

- Integrated.
- Unified.
- Unique.
- Systematic.

Here, integrated means all physical domains in the system are considered together (i.e., concurrently or simultaneously). This is needed because, typically, there will be dynamic interactions among the physical domains.

Unified means that all physical domains are treated using similar (i.e., analogous) methodologies. No matter what the physical domain is, it will have two types of variables: through-variables and across-variables. Through-variables propagate unchanged through an element. Examples of through-variables are force, current, fluid-flow rate, and heat-transfer rate, which are all analogous. Across-variables are defined across a physical element, at one end (action end) with respect to the other end (reference end). Examples of across-variables are velocity, voltage, pressure, and temperature, which are all analogous. There are two types of sources (inputs) in a system: through-type (T-type) sources whose independent variable is a through-variable, and across-type (A-type) sources, whose independent variable is an across-variable. Examples of T-sources are force source, current source, fluid-flow source, and heat-transfer source. Examples of A-sources are velocity source, voltage source, pressure source, and temperature source. In view of these analogies, series-connected physical modules behave similarly across physical domains, and also parallel-connected physical modules behave similarly across physical domains. Approaches that exploit these analogies are indeed unified approaches.

Unique implies that at the end of the process (typically, modeling or design of a system), only a single result (a model or a design) is generated. Since an engineering system may have more than one model and more than one design, in order to yield a unique end result, the employed procedure needs to be "optimal" in some sense. So, among the possible models or designs, the mechatronics approach should provide a way to make the best choice.

Systematic means that the underlying procedures need to be well-articulated and follow a clear set of steps. Then, there will not be any confusion as to what procedures (or program sequences) need to be followed in order to yield the end result. This also enables the software engineers to develop proper computer programs to carry out the underlying procedures.

The features of being integrated, unified, unique, and systematic should be necessarily possessed by proper "mechatronics" approaches of modeling, design, and instrumentation (including control) of an engineering system and, by extension, also of a quantum mechatronics system.

It can be confirmed that a mechatronics product that is consistent with the enhanced characteristics indicated above, will possess the following benefits:

- Optimality and better component matching.
- Increased efficiency.
- Cost effectiveness.
- Ease of system integration and expansion/enhancement.
- Compatibility and ease of cooperation with other systems.
- Improved controllability.
- Increased reliability.
- Increased product life.

1.2. Quantum Technologies

The field of quantum technologies (in the sense of possessing genuine quantum effects, such as entanglement and superposition) emerged in the past few decades as a disruptive area that may provide significant advantages in the processing and transmission of information, as well as sensing and measurement in physical systems [5]. Quantum computers promise to carry out exponentially faster computations in areas such as quantum simulation as well as factoring in cryptography.

Quantum technologies are applicable to the microscopic domain, which behaves quantum-mechanically. Among others, atomic, molecular and quantum optical systems, as well as solid state systems in the genuine quantum realm, such as superconductors and quantum dots, are some of the quantum platforms experimentally studied.

For digital quantum processors, two quantum technologies have special prominence: superconducting circuits and trapped ions. They allow for efficient single- and two-qubit gates, which constitute a universal set for arbitrary quantum operations. They can also be initialized and measured with high fidelities. However, for our practical purposes, when aiming at connecting the fields of mechatronics, a mechanical engineering area, and quantum technologies, a more direct quantum platform to consider is that of quantum photonics. This technology employs the quantum particle of light, the photon, as a carrier of quantum information. The latter can be encoded in horizontal and vertical polarization states of each photon, which constitutes a qubit, or in other degrees of freedom, such as dual rail or time-bin encodings. Photons can interact via nonlinear media, such as parametric down-conversion crystals, or Kerr devices. They can, in this way, become entangled, and be used, for example, in Bell tests for nonlocality. For a review on this field, see Ref. [6]. Photons can propagate at long distances with almost no decoherence, preserving their genuine quantum properties of superposition and quantum entanglement. They can also be efficiently connected to macroscopic devices via single-photon sources and detectors. Therefore, they constitute a natural candidate to establish quantum links between macroscopic systems such as robots, drones, or both. One should clarify here that the quantum links we refer to are photons that can be entangled before they are detected by the robot and/or drone detectors. Once measured, the entanglement and quantum properties disappear, as the robotic systems are macroscopic and cannot sustain genuine quantum features, such as coherence and entanglement. However, shared optical entanglement can lead to a host of quantum communications applications. The most accessible is in the field of quantum cryptography, such as establishing secret key bits via quantum key distribution (QKD). QKD provides a provable information-theoretic security model [7], which distinguishes itself from the computational security associated with traditional key distribution systems. A longer-term application of distributing entanglement could be to enhance the sensitivity of distributed sensor systems [8,9]. Classical sensing systems can use mobile platforms to optimize sensor positions [10], but extending the sensor network capabilities to allow for shared entanglement can, in principle, allow much more sensitive measurements. In such a scenario, the optimal sensor location depends, in part, on the entanglement resources available and other system-level parameters, such as loss between the sensors.

The union of quantum technologies and mechatronics can possess the features of being integrated, unified, unique, and systematic, exposed above in the area of mechatronics. The combined field is integrated because it considers a unified system involving classical, macroscopic devices (e.g., robots and/or drones) and quantum systems (e.g., photonic quantum channels, entangled photons). It is also unified, given that one has to treat them under a common framework, connecting the photonic systems with the classical platforms via single-photon sources and detectors. It can be also unique in the sense that one may look for the most efficient design when considering both classical macroscopic systems and quantum platforms. Finally, the methodology in quantum technologies is generally systematic and can also be in this context, when relating them to classical autonomous systems.

1.3. Quantum Mechatronics

In this review article, we describe recent results in the literature connecting the fields of mechatronics and quantum technologies, in the sense exposed above, in a novel area that we call "quantum mechatronics". We describe three different aspects inside this area. In Section 2, we review results exploring the possible connection of robotic systems via photonic quantum channels, for enhanced security, sensing, and communication. In Section 3, we describe the results that study the possible control of macroscopic systems via quantum effects. In Section 4, we review recent efforts for enhancing the education of mechanical engineers upgrading the courses with quantum technologies, both in theory and experiment. Finally, we give our conclusions.

We point out that a previous work was published with the same title as this article in Ref. [11], although our definition of quantum mechatronics differs from that work, which is more related to nanoelectromechanical systems.

2. Quantum Technologies in Robotics Systems

In the field of quantum technologies in robotics systems, a series of works have been produced. Here, we succinctly describe them.

In Ref. [12], it is shown that collaborative robotic tasks of unmanned systems can be performed in a network, where the agents are entangled. For example, the leader robot generates two polarization entangled photons, sending one of the pair of photons to each of two follower robots and/or autonomous vehicles. The follower robots measure these photons in a locally chosen polarization direction. These measurements result in computable correlations between the measurements, for instance, perfect correlations when the two users choose the same basis state and no correlations when they choose orthogonal basis states. Note that in this case, the users can pick any arbitrary polarization basis state, and as long as they "match", correlations will be high. The resulting correlation characteristics cannot be described by classical probability theory with local realism, as they arise due to the quantum connection between the spatially-separated photons. Entanglement can subsequently be used for QKD or other quantum communications applications. The first experimental steps to realize this concept were described in Ref. [13].

Ref. [14] describes the use of quantum entanglement and cryptography for automation and control of dynamic systems, understood as systems where the rate of change of its state variables is sizable. Quantum entanglement is proposed to be realized by spontaneous parametric down-conversion of photons. Two "entangled" autonomous systems may exhibit correlated behavior without any classical communication between them because of the quantum entanglement phenomenon. In an automation scenario, the "Bob Robot" shares quantum correlations with the "Alice Robot", being that Bob and Alice are the two parties involved. Even though macroscopic systems cannot be entangled, they can still communicate with each other via entangled photons and therefore, share genuine quantum correlations, enabling many applications. Quantum cryptography allows, furthermore, for guaranteed security. These capabilities may be implemented in the control of autonomous mechanical systems where, for example, an "Alice Autonomous System" can control a "Bob Autonomous System" via sharing distributed quantum keys.

In Ref. [15], the application of quantum teleportation to the control of classical dynamic systems and autonomy is proposed. Quantum teleportation is a genuine quantum phenomenon, and was first described in how to teleport an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels in Ref. [16]. In this paper, the possibility of applying this quantum technique to autonomous mobile classical platforms in order to enhance control and autonomy is proposed.

Ref. [17] introduces a procedure for automating the photon quantum experiments for mobile robotic applications. In parametric down-conversion experiments with entangled photons distributed between robots and/or drones, motorized optics equipment may align the photon sources to the detectors on the mobile robots in an automated way. This automatic alignment process is among the key enabling technologies for integrating quantum capabilities for the control of mobile robotic systems. In this paper, the automated alignment is studied, while analyzing the uncertainties in the dynamics of the system that may potentially make the alignment task highly challenging.

Figure 1 shows an image of two quantum robots, Alice Robot and Bob Robot, prepared for sharing entangled photons. This way, they may establish secure communication among them. This is similar to the research described in Refs. [12–15,17].

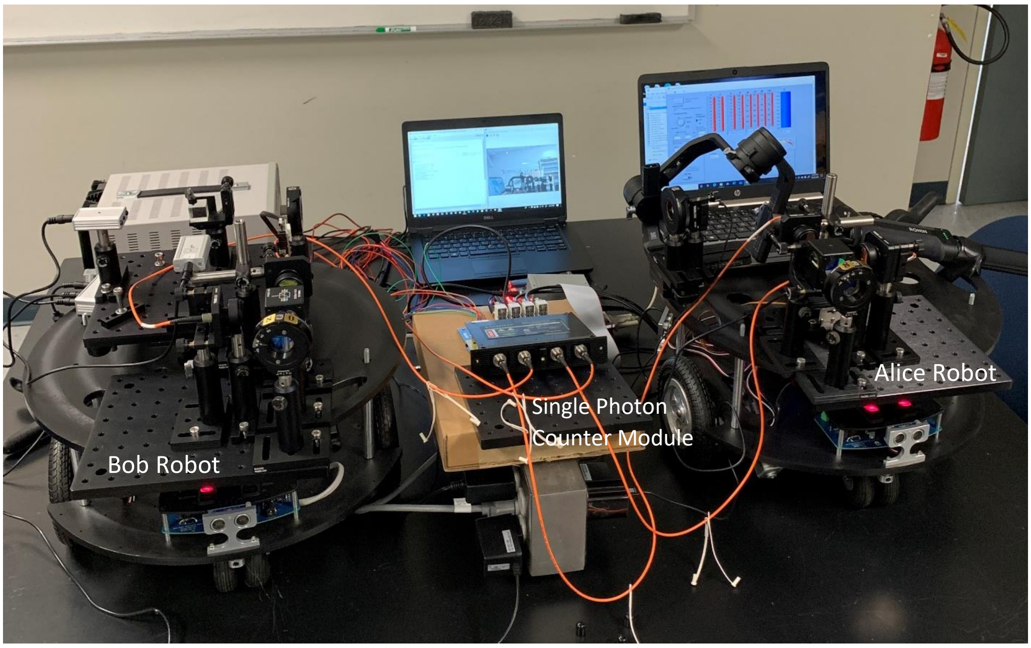

Figure 1. Image of robots prepared for sharing entangled photons. Similar to preliminary theoretical and experimental developments of quantum robotics of Refs. [12–15,17].

Arguably, there are going to be many issues when trying to translate experiments, such as teleportation, that were previously performed on a bench or in fiber to mobile robots. These challenges can be listed as areas of future work that need addressing, together with the potential technologies that can help meet these needs.

For instance, the teleportation experiments require "interference" between photonic wave-packets. This is much harder than a typical one-direction QKD measurement, and sophisticated distance/timing controls need to be integrated into the systems. The resolution required on these controls depends on the inverse of the photonic wave-packet bandwidth, creating various trade-offs in system design. Integrated optics is one potentially important technology for long-term realization of the needs in a small SWAP (size, weight, and power consumption), which is, of course, critical for implementation in drones. Important progress is being made in creating quantum optical resources with low SWAP [18]. Noteworthy in this direction for use on robots/drones is the work on CMOS-compatible silicon photonics, which has the potential to match the SWAP of conventional electronics [19]. A chip-scale photon-pair source fabricated in a commercial 45-nm CMOS process is described in Ref. [20]. However, in that work, only the quantum photonics aspects are demonstrated in a device that is passive from the electronics standpoint. Recent progress on integrating electronic controls on the same CMOS chip to demonstrate the first step toward full photonic/electronic integration will be presented in an upcoming conference paper [21].

If quantum signals are eventually to be distributed over long distances through the atmosphere, then temporally-varying loss due to turbulence and pointing-and-tracking errors need to be addressed. While quantum signals are generally much more sensitive to loss than classical signals, in some cases, variable loss from turbulence can be somewhat less problematic for quantum signals [22]. This stems from the performance metrics associated with traditional free-space communications, such as the probability of a "fade" leading to an unacceptable bit-error-ratio or a loss-of-lock, being dependent on the high-loss tails of the turbulence-induced transmission function [23], while the performance metric of the quantum bit-error rate is more closely related to the mean loss [24]. The ability of some quantum systems to post-select the time-periods of low loss means that as long as the transmission sometimes exceeds a performance threshold, then quantum communications remain possible [24,25]. The same argument also appears valid for pointing-and-tracking errors.

3. Macroscopic Actuators via Quantum Effects

The field of quantum effects acting on macroscopic systems has also produced a series of works, from which we describe some aspects in detail in this section. More generally, a whole area of quantum optomechanics has emerged in the past decade or so, with related references reviewed, for example, in Ref. [26].

In Ref. [27], various macroscopic mechanical effects of light are presented. These effects are a consequence of the conservation of energy and momentum during the interaction of atoms with an electromagnetic radiation field. Examples include the following: (a) atomic deflection, which takes place when an atom at rest absorbs or emits a photon from a light beam, with the resulting transfer of recoil momentum manifesting as an absorptive force in the same direction as the light beam; (b) laser cooling, in which atoms in motion illuminated in opposition of phase by a light beam can be slowed down to large levels of equivalent damping as a frictional effect, i.e., the atom is decelerated; (c) atomic diffraction, which takes place when a beam of atoms interacts with the periodic structure of a standing wave, resulting in diffractive scattering, which is analogous to the scattering of a light wave by a grating; and (d) gradient forces, in which an atom can be confined or guided by a light beam in a potential field generated by a limiting potential. Uses of these techniques for the realization of quantum computation hardware are described in Ref. [5], particularly harmonic oscillator, an optical photon, cavity quantum electrodynamics, ion traps, and nuclear magnetic resonance.

Optical tweezers and ion traps are examples of phenomena at a quantum scale, where a macroscopic system response is caused by micro and quantum interactions, which can be observed and utilized at macroscopic scales, more notably in quantum optics experiments, as macro-level actuators (motors) that can generate macro-level forces and torques. In these examples, particle acceleration and trapping by gradient and scattering forces and torques are the most evident, observable, and measurable of these optomechanical interactions. For example, in experiments described in Ref. [28], particles experienced two optical forces: a scattering (levitation) force along the beam axis and a gradient force resulting from a non-uniform spatial distribution of light (for example, in the vicinity of the beam focus), enabling macroscopic guidance and control of small particles under a light beam. Today, higher-order Gaussian or Bessel-mode beams and unusually shaped particles are used, but the most promising technique is the trapping of low-index particles with an optical vortex (Ref. [29]).

Finally, as an example of macroscopic actuation va quantum effects, in Ref. [30], the nonlinear optical properties of a cloud of micron-sized particles, confined inside a volume and shaped into a specific surface by electromagnetic means with coherent laser illumination, are investigated theoretically and experimentally. This new application of scattering and gradient optomechanical forces enables the forming of a very large and lightweight aperture of an imaging system, hence reducing overall system mass and cost for future applications, such as space telescopes.

4. Education in Quantum Mechatronics

With respect to the area of education in quantum mechatronics, a couple of articles are published.

Ref. [31] proposes to extend a typical mechatronics course beyond standard engineering topics and to modernize it with complementary quantum engineering aspects. With the recent fast advances in quantum technologies, such as quantum computers, communication, sensing, and algorithms, it is of the utmost importance that the next generation of engineers be trained in quantum technologies, which will prepare them for future careers in the ever-changing industry in these areas. To enhance the education of the future engineers in such areas of significant relevance, quantum entanglement and quantum cryptography experiments, as two basic topics in quantum mechanics, are brought into the mechatronics course in an initiative reported in this article. An innovative online remote proof-of-principle demonstration of such quantum experiments is also developed in this work.

In Ref. [32], opportunities for linking research and teaching via service-learning as an experiential teaching method are studied. This combines community service with research and academic tasks, particularly in the context of mechatronics and dynamic systems areas. The article is not only focused on quantum mechatronics, but it also includes diverse advanced technologies related to mechatronics systems, namely, energy harvesting systems, self-powered solar unmanned aerial/ground vehicles, bio-inspired vertical axis wind turbines, biologically inspired mechanical birds and insects, and jelly-fish inspired propulsion, as well as the quantum-related ones, namely, nature-inspired techniques, such as quantum networks, cryptography, and entanglement for multi-robotic and vehicle systems. Connecting university instructions to real-life applications and advanced technologies, as research-informed service-learning tasks, results in an attractive and engaging as well as rewarding experience for the students.

One of the educational contributions of these works in mechatronics is that they are targeting the students in mechanical/electromechanical/aerospace engineering fields who are not traditionally exposed to any quantum mechanics topics. This is different from the existing programs in quantum computing that electrical/computer/physics programs offer, related to quantum computing/algorithms/computers.

5. Conclusions

Mechatronics systems and quantum technologies are starting to merge in a novel research area, namely, quantum mechatronics. In this review article, we have described initial steps in this respect, including developments in quantum robotics and macroscopic actuators via quantum effects, as well as educational initiatives in quantum mechatronics. We are convinced that this is a promising research avenue that may produce highly disruptive and practical applications, both in engineering and in quantum science.

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