DESIGN OF FOAM COVERING FOR ROBOTIC ARMS TO ENSURE HUMAN SAFETY

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ABSTRACT

Unintentional physical human-robot contact is becoming more common as robots operate in closer proximity to people. This contact may generate a large impact force and cause severe human injuries. Therefore, the ability to reduce the human-robot impact force and ensure human safety is a fundamental requirement for human-friendly robots. An easy and effective way to achieve this is using foam to cover the robot surface. We present a method for designing the stiffness and thickness of the foam covering based on a realistic safety threshold and an improved impact force model. Our model incorporates the previously neglected coupling of the human head to the torso and the coupling of the robot arm to its base. The impact model and model-based design procedure are experimentally verified for various foam properties, and robot and human velocities. The impact experiments are performed with an apparatus simulating the human head and, at lower velocity, with a human volunteer. The maximum error between the predicted and experimental peak impact force results is 8%.

1. INTRODUCTION

Whether in industrial applications such as teach programming, or service applications such as rescue robots, robotic manipulators are operating closer to humans than ever before. The close proximity of humans and robots makes unintentional contact likely. This contact could generate a large impact force and cause serious human injury. Therefore the ability to reduce the human-robot impact force and ensure human safety is a fundamental requirement for these robots. Some researchers have employed control algorithms for reducing this force [1]–[3]. These controllers are fundamentally limited by the delay due to finite sampling frequency, low actuator bandwidth and actuator saturation. Other researchers have developed sophisticated actuation approaches to reduce joint stiffness and the impact force [4]–[6]. These approaches, while beneficial, are relatively expensive to implement and maintain, which limits their applicability. Using foam to cover the robot arm surface is a simple and effective way to reduce the impact force, and may be applied to conventional robots and newly designed robots. Due to its passivity, it is much less affected than active solutions by power failures, control system faults and varying environment conditions. In addition, foam reduces the stiffness of the robot surface to moderate the impact force rather than reducing the joints stiffness that could decrease trajectory tracking ability [4].

Currently, foam has been used for human-friendly robot designs in [7]–[9], and also for head protection in helmets [10]–[14]. In [7] and [8], an approach was presented for selecting the elastic modulus and viscosity coefficient of a foam covering to ensure the human-robot orthogonal-impact force was smaller than the pain tolerance of the human body (specified as 50N). However, they assumed the human and robot velocities were constant throughout the impact; and ignored the mass and stiffness values of both the human body and the robotic manipulator in their impact force model. This made their simulation results unrealistic for most cases. They did not present any experimental results. They mentioned the importance of knowing the minimum foam thickness required to avoid it becoming fully compressed but did not provide a method for finding it. In [9], a better human-robot impact dynamic model was proposed. The manipulator was modeled as a single degree of freedom prismatic joint driving a mass, representing the rotor. The rotor mass was coupled by a spring and damper to a 2^{nd} mass, representing the link. The human's head was modeled as a point mass, and the compliant covering was modeled as a compression spring. The rotor and the human head were assumed to be free masses. This is unrealistic since the head and rotor are not actually free masses. The researchers' focus was on the use of a varying stiffness transmission to reduce impact force. They did not study compliant coverings in any detail.

The impact force with foam-lined helmets was modeled as the force of a compressive spring in parallel with a damper in [10]. Using this model, they demonstrated that helmet materials with lower stiffness helped to reduce the impact force. Later, they presented a simplified model of the foam without the damper [11]. They employed the standard Head Injury Criterion (HIC), described further in section II, to evaluate the safety of given foam. Some researchers chose finite element analysis to model foam-lined helmets [12]–[14]. This technique can provide greater realism but does not provide useful equations for foam design.

While it is intuitive that the softest foam will produce the smallest force, the required foam thickness would be impractical. In this paper, we will demonstrate that a relatively thin layer of stiffer foam can satisfy the human-robot safety requirement. In the next section we determine a realistic threshold for preventing human injury. We present a more detailed impact force dynamic model that incorporates the coupling of the human head to the torso and the coupling of the robot arm to its base in section 3. Model-based methods for determining the maximum and minimum bounds of the foam stiffness are presented in sections 4, respectively. Then, the procedure for foam design is summarized. Predicted and experimental impact force results are compared in section 5. Conclusions are drawn in section 6.

2. DETERMINATION OF THRESHOLD FOR PREVENTING HUMAN INJURY

Two types of human injury criteria have been used by previous researchers. In [6]-[8], if the impact force is smaller than 50N, the impact is considered safe. However, this is only used when the impact velocity is 0.6 m/s or less. We wish to include the case

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