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Experimental tests in human–robot collision evaluation and characterization of a new safety index for robot operation

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ABSTRACT

This paper describes an experimental procedure consisting of impact tests that simulate a collision of a human head with an industrial robot with the aim to validate a safety index named as New Index for Robots (NIR) and its outputs. The experiments in this paper are based on lab tests. It is an attempt to characterize the NIR index underlying the main parameters that are involved in crash interaction and to highlight limitations and weakness of suggested impact tests.

1. Introduction

The term "service robot" that was tentatively defined by the International Federation of Robotics (IFR) as "a robot which operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations" has now a more adjusted definition included in recently approved ISO 8373: 2012 Robots and robotic devices: vocabulary. According to this new vocabulary, a "service robot" is a robot that performs useful tasks for humans or equipment excluding industrial automation applications and it can be distinguished between service robot for personal use (used for a non-commercial task, by a lay person) and service robot for professional use (used for a commercial task, by properly trained operator) [1].

The close interaction among service robots and humans makes safety constraints one of the most significant aspects of robot design and operation, including not only the aim of avoiding collision, but also of investigating and minimizing consequences of collisions, that are caused by fast or unforeseen movements of robots.

Abbreviations: IFR, International Federation of Robotics; WSTC, Wayne State University Concussion Tolerance Curve; NIR, New Index for Robots; GSI, Gadd Severity Index; HIC, Head Injury Criterion; AIS, Abbreviated Injury Scale; EuroNCAP, European New Car Assessment Program; GAMBIT, Generalized Model for Brain Injury Threshold; SIR, Safety Index for Robots.

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Although reduction of collision consequences has been widely explored in the field of safety in automotive (performing crash tests by using different models to simulate human body), the results of car industry cannot be directly extrapolated to impact studies among robots and humans. Nevertheless it can be used as a good base to compare with.

Intrinsic safety design in robots for industrial use is still a matter of discussion in industrial manufacturing fields, where mechanical risks have been traditionally avoided by using adequate protections that are linked either to robot design or indirectly to the robot operational process, like for example by putting physical barriers between robot and operators.

However, this situation changes as long as there is closer interaction between human and robots. Even if some standards [2,3] define new collaborative operation requirements for industrial robots (minimal speed, maximum dynamic power or maximum static force), the lack of specific standards for service robots needs to be covered by new viewpoints [4]. In general a service robot is understood as a robotic system with a certain level of autonomy in performing service operations for given tasks within a specified environment and interaction with human users, while industrial robots are devoted to predefined operations in industrial tasks that are very often well-structured environments [2]. Peculiarities for design and operation of service robots are outlined in [5] with a special attention also to safety issues much more than in industrial robots.

Safety is then an issue of increasing importance mainly when robots interact or collaborate with human users. Basic rules for industrial robots, as in [2] needs to be enlarged when humans may have risk in interaction with robots. Main factors for safety issues are related with risks of impact of robot part with human body or part of it, not only in malfunctioning of the systems but more and more in the operations with strict interaction between robot and human operators, as reported in [4].

Several strategies have been developed to study biomechanics in the brain injury [6], through experimental, mathematical or observational approaches, and to link it to appropriate safety criteria [6–9]. According to those theories, which were based on the experience of crash tests in automotive industry, several indexes have been empirically formulated to link quantitative injuries with safety levels of robots. Examples of these indexes in Robotics are described in [10–12].

But the main limit of these extrapolated indexes can be considered that most of them have been mainly evaluated by means of mathematics or simulation programs (LS-DYNA) [13,14] whereas only a few have been assessed by using test devices [15] (first experimental evaluation of HIC, at an automobile certified crash-test facility using DLR lightweight robot III and a Hybrid III dummy). The need of using experimental measure in safety evaluation of robot operation has been also stressed in [16] where impact tests with a seven-degree of freedom flexible joint robot (Lightweight Robot III) of 14 kg against a Hybrid III crash test Dummy were performed.

The aim of the experiment reported in this paper is to setup an appropriate scenario to reproduce a basic collision between industrial robot and human in a proper way so that the outcomes can be used to check the implementation of the New Index for Robots [17], which is one of aforementioned safety indexes in robotics field, with a comparison with one of the most globally recognized index in [18]. Moreover, one of the contributions of the reported experiments is an experimental evaluation of the proposed new index for robots in a proper testing frame with suitable setup and sensors.

The appropriate scenario has been conceived by looking at the main aspects of impact and robot actions together with possibility of a fairly simple laboratory set-up for tests that have been performed also for a validation of the proposed new safety index. This fairly simple laboratory set-up has been arranged with details that are reported in [15]. The characteristics of the laboratory set-up can be summarized in using an industrial robot as the available ADEPT SCARA robot with fairly simple models of human body parts with sensors that are installed both on the robot arm and model surfaces.

The rest of the article is structured in the following way. Section 2 introduces different approaches that were developed from earlier 1960s of safety indexes. It also introduces the first indexes proposed in robotic fields. An experiment lay out that was setup to perform the tests is described in Section 3, where software & hardware and experiment restrictions, such as speed conditions or impact point locations are explained for final test execution. Section 4 summarizes the outcomes and results of final test cases. Finally, conclusions from the experiment are highlighted in Section 5.

2. Safety index and experimental evaluation

A summary of main existing safety indexes is outlined in this section. These are the formulations that are the most related ones to the herein proposed experiment procedure. The first four indexes belong to investigations for automotive fields, since those are based on a long experimental activity.

In the 60s Lissner introduced the Wayne State University Concussion Tolerance Curve (thereafter WSTC) [8] that represents the maximum acceptable acceleration versus time of impact. The failure criterion was the skull fracture and/or concussion in the head of cadavers that were tested against a flat surface. The resulting curve is based on three main parameters, such as acceleration, temporal pressure and time of impact in seconds. Later, Gurdjian and Patrick [9] improved the index, by using more experimental data. This is considered the foundation for most currently accepted head injury indexes.

The Gadd Severity Index [7] that was obtained from the WSTC is again an expression of the head acceleration response as function of the impact with pulse duration. In fact, a is the average acceleration of the pulse of interest and n is assumed in general as 2.5 [7,19], so that the index is expressed as:

$$GSI(a) = \int_0^T a^n dt. \tag{1}$$

Values of GSI > 1.000 are considered to be dangerous for life (injury with un-survivable effect) [7].