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研究課題名（和文） 単一故障検知機能をもつロボットとの最悪条件下での衝突時における新たな安全制御戦略

研究課題名（英文） Novel safety control strategy at the time of collision under the worst condition for a robot with a single fault detection capability

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研究成果の概要（和文）：本研究では、単一故障検出が可能な冗長自由度を持たないロボットが暴走した場合でも、手のツール先端が人間との接触運動をフェイルセーフに維持できる運動空間、フェイルセーフ（FS）接触運動空間を提案し、FSの有効性と限界を論じた。人間-ロボット協調システムにおいて、統計的にロボットとの接触頻度が最も高い人間の手が、最悪の条件でロボットに衝突する場合を実証実験の対象とした。本研究では、FS接触運動空間が適用できるマニピュレータにおいて、ロボットとの接触による運動量を軽傷レベルの人肌の重篤度までに抑えるための接触運動制御手法を明らかにし，ダミー指にてこの制御手法の有用性を検証した。

研究成果の学術的意義や社会的意義
While previous industrial robots could not perform tasks that require continuous contact with the human body, a human and a robot form a cooperative system, contact with the human will be allowed without fear of runaway, and thus the availability of the robot is expected to be extremely high.

研究成果の概要（英文）：We propose a fail-safe (FS) contact motion space, a motion space in which the robot hand's end tip can maintain fail-safe contact motion with the human even when a robot without redundant degrees of freedom capable of single-fault detection runs out of control, and discuss the effectiveness and limitations of FS. In a human-robot cooperative system, the case in which the human hand, which statistically has the highest frequency of contact with the robot, collides with the robot under worst-case conditions was the subject of empirical experiments. In this study, we identified a contact motion control method for manipulators to which the FS contact motion space can be applied to limit the momentum due to contact with the robot to the severity of human skin at the level of minor injuries, and verified the usefulness of this control method with a dummy finger.

研究分野： ロボティクスおよび知能機械システム関連

キーワード： Fail-safe　Dummy finger　Minor injury　Contact motion　Runaway space　Worst-case conditions　Momentum control

１．研究開始当初の背景

Research on robot safety has been largely categorized into pre-collision and post-collision, and has been discussed separately. Recently, some studies integrating pre-collision and post-collision issues have been reported. This is an approach that estimates and evaluates the severity of injuries in the event of a collision before the collision, while taking into account the dynamic and diverse contact conditions between the two parties. Although robot motion planning is performed and executed based on a priori inferences about whether it is safe or not, it is implicitly accepted that robot operation should be halted in the event of robot failure or for unforeseen circumstances caused by human error, as safety cannot be confirmed. The academic question for this study, then, is "Is there any other strategy than to stop the robot in the event of a failure?" is "Is there any other way than to stop the robot in case of a malfunction? For the case where the human and the robot are not in contact, kinematic discussions have already been conducted and standardized on how long the robot should run in the air, and the applicants have even made a proposal to compensate for the inadequacy of the standard (potential runaway space, described below). However, it has been considered reasonable to slow down sufficiently during normal operation to minimize the runaway distance and to use a stopping strategy in unintended situations, because this small amount of runaway distance can cause serious injury to humans when the two vehicles are in contact with each other. This study proposes to question this strategy and to explore other safety measures. If the robot does not have to stop in the event of a malfunction, the margin between the two can be reduced, and since the deceleration norm just before a collision can be explicitly given, the robot speed can be increased during normal operation, which is expected to contribute to increased productivity while ensuring safety.

２．研究の目的

This research theoretically constructed a “fail-safe contact motion space”, which is a control criterion for a safe operation where a robot in contact with a human can secure the safety of the human even if a single failure occurs so that the robot runs out of control. The space in which the robot can continue the safe contact motion for a short period after failure detection is defined in the level of the supplied energy that does not cause internal bleeding of the skin, which was obtained in the verification experiments using the soft tissue of animals as a substitute for the human soft tissue. In addition, a dummy of the impacted human soft tissue was developed, and the contact force during the fail-safe contact motion is compared with the safety verification data to confirm the validity of the ail-safe contact motion space when the robot performs the contact motion.

The originality of this study is to improve the ability to restrain risk by incorporating a new control strategy that continues the operation of the robot by maximizing the use of the no-fault joints in the case of a single fault, rather than simply stopping the motion of the robot. The creativity of this study is shown in the control strategy that can continue the operation of the robot for a short time to further expand the safe state, which is completely opposite to the conventional method in which the emergency stop is triggered in the case of a fault to secure safety.

３．研究の方法

We discussed the algorithm for the minimum volume enclosing dynamic manipulability ellipsoid under the condition of a single fault in [1][4]. We then conducted psychophysiological experiments for replicating a dynamic worst-case clamping scenario, where the human hand was clamped by a fixed obstacle and an approaching end effector of a robot. The dynamic response of the contact force obtained through the impact experiment [2][3] was analyzed using the proposed nonlinear viscoelastic model, and the viscoelasticity of human hands was quantified using five viscoelastic parameters, which was used for human hand dummy development [2]. We also discussed, in parallel with the analysis of the viscoelasticity of the human hands, such injuries with high severity as abrasion, crushed/contused wound, laceration, and avulsion when the robot end tip contacts the dorsal side of the human finger. Finally, we proposed a control strategy for manipulators to secure the safety of human hand parts in the clamping scenario [5][7], where the controller for achieving the strategy comprised three parts: controller loop, momentum observer, and motion reshaping. While the above component-wise methodologies satisfy part of the original goals, all of them were not necessarily achieved:

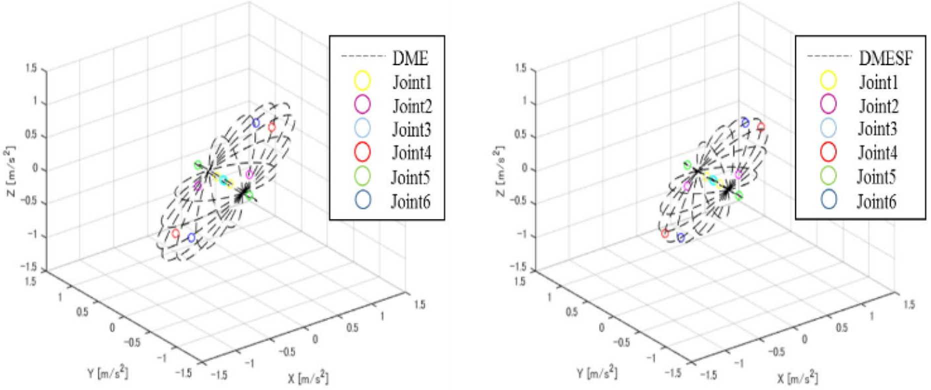


Figure 1　　DME and DMESF for configuration 4

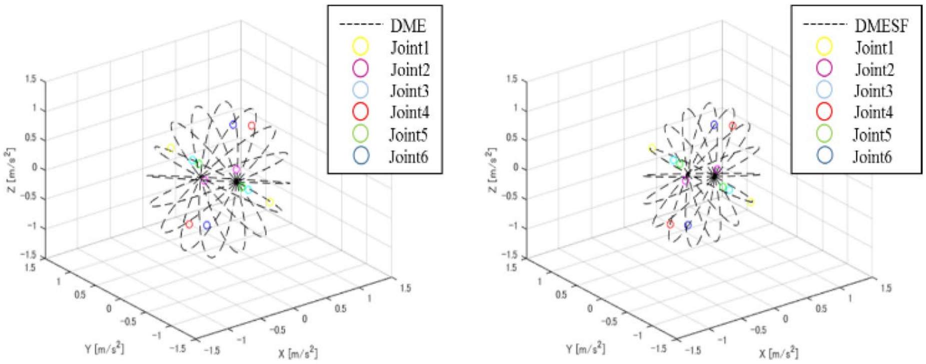


Figure 2　　DME and DMESF for configuration 5.

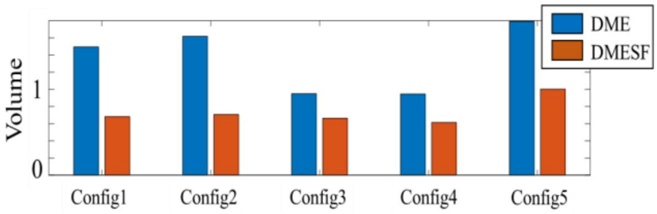


Figure 3　　Comparison of volumes.

４．研究成果

Figure 1–Figure 2 show the DME and DMESF comparisons for each configuration. The axes of each graph show the directions of acceleration, and the coordinates for each graph are the same as the basic coordinate of KUKA. The circles depict the acceleration, x ̈_(i+), and x ̈_(i-) where i=1,2,..,n, and the broken lines denote the DME and DMESF in their respective graphs. From these results, it can be seen that the DMESF is enveloped by the DME in all configurations. A comparison of the volumes is shown in Figure 3.The vertical axis shows the volume of the ellipsoid and the horizontal axis shows the configurations. The blue bar represents the DME and the orange bar represents the DMESF. From this result, it can be gauged that the volume of the DMESF is smaller than that of the DME under all conditions.

After confirming the effectiveness of DMESF, the limitation is discussed by quantifying the performance in terms of the depth in the contact motion direction. Figure 4 shows a sample of the depth

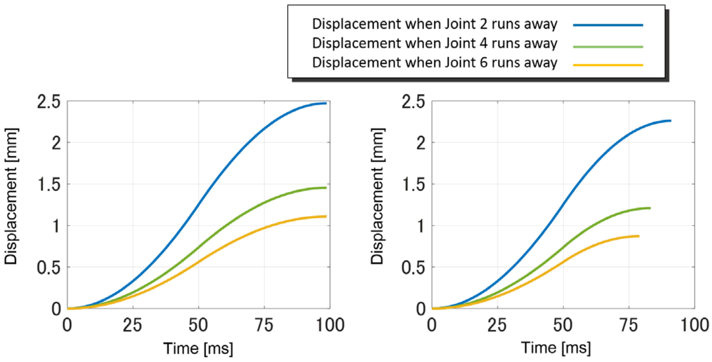
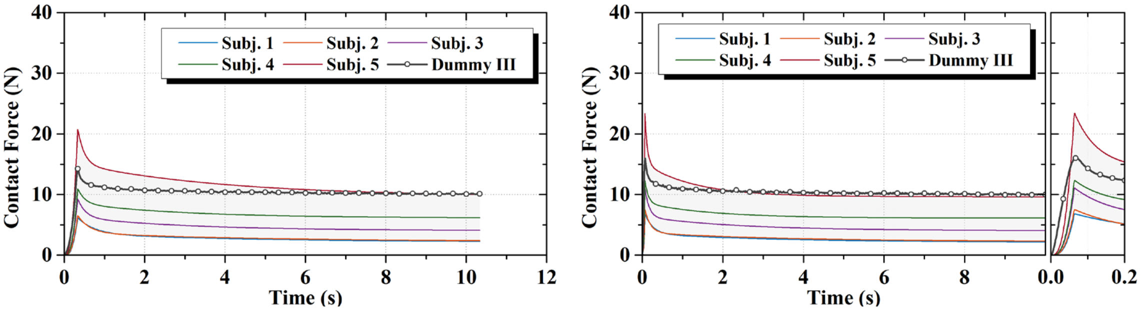


Figure 4　 Simulated result (Config.I, 0 mm/s, left=w/o AJ, right=W/ AJ)

which is dependent on the contact speed as well as the run-away joint. Therewith, we conclude that it is risky enough to use human skin pieces stocked in the bio-bank to evaluate the damage in the contact motion and decide to develop dummy skin instead.

Figure 5 shows the results of a dummy development for Dummy III and forefinger pads. At the beginning of the rising phase, the contact forces of Dummy III exceeded those of the human subjects; however, they entered into the force variation range at the end of the rising phase, as were observed in Figure 5(b). This is consistent with the observation that all three artificial dummies show a higher elasticity when the compressive displacement is small.



(a) contact velocity of 10 mm/s and steady-state force of 10 N (b) 250 mm/s and 10 N

Figure 5 Comparison between Dummy III and human soft tissues on viscoelasticity. In (a)–(b), contact force variations of the Dummy III were obtained by measurement, while those of five human subjects were computed using the nonlinear viscoelastic model and mean values of the nonlinear viscoelastic parameters. The light gray region denotes the force variation range. In (b), the graph on the right side shows the rising phase. The abbreviation “Subj. 1–5” is for “human subject 1–5” in the legend.

The reshaped motion command is illustrated in Figure (a). The motion command was set as 60 mm from 2.5 s to 7.5 s, i.e. a compressive displace-ment of 10 mm was maintained for 5 s. The estimated external momentum increased from 2.5 s owing to a positive contact force, and exceeded the predetermined momentum injury criterion of 10 N·s at approximately 4.4 s, as shown in Figure 6(b).

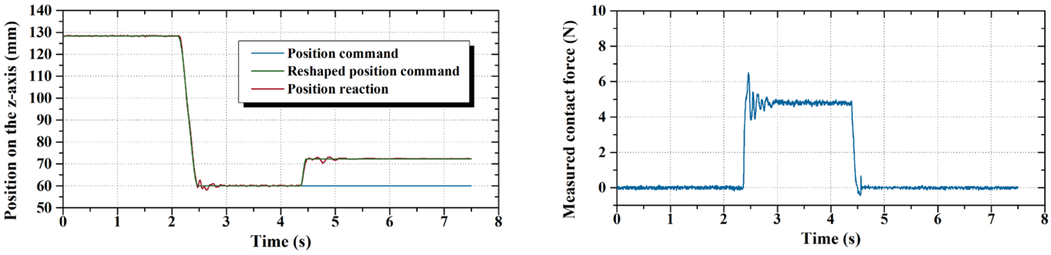


Figure 6 Reshaped position command and contact force of pattern III. (a: left) Position command, reshaped position command, and position reaction along the z-axis. (b: right) Contact force along the z-axis measured by the force sensor.

An additional experiment was conducted to illustrate the effectiveness of the momentum injury level the result of which is shown in Figure 7. The proposed control strategy can limit the external momentum under a predetermined momentum injury criterion, and the above analysis shows that the momentum, that is, the integral of the contact force, can be regarded as a compatible injury criterion. Therefore, the control strategy performs the ability to secure the safety of the human soft tissue at an impact.

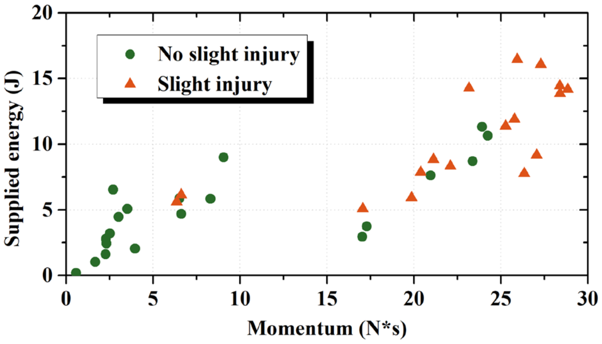


Figure 7　Relationship between the momentum, supplied energy, and state of slight injury.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　2件）

１．著者名 Kim, E., Yamada, Y., Okamoto, S., Sennin, M., Hiroki, K.	４．巻 67
２．論文標題 Considerations of potential runaway motion and physical interaction for speed and separation monitoring	５．発行年 2021年
３．雑誌名 Robotics and Computer-Integrated Manufacturing	６．最初と最後の頁 102034,
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.rcim.2020.102034	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Jian Liu, Yoji Yamada, Yasuhiro Akiyama, Shogo Okamoto, Yumena Iki	４．巻 11
２．論文標題 Development of Dummy Based on Impedance Properties of Human Soft Tissue Using a Nonlinear Viscoelastic Model	５．発行年 2023年
３．雑誌名 IEEE Access	６．最初と最後の頁 7782, 7793
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2023.3237763	査読の有無 有
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〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　5件）

１．発表者名 Yumena Iki, Yoji Yamada, Yasuhiro Akiyama, Shogo Okamoto, Jian Liu
２．発表標題 Designing A Dummy Skin by Evaluating Contacts between A Human Hand and A Robot End Tip
３．学会等名 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)（国際学会）
４．発表年 2020年

１．発表者名 Hiroki Kito, Yoji Yamada, Jian Liu, Shogo Okamoto
２．発表標題 Updating Potential Runaway Motion Volume in Task Space and Introducing Minimum Volume Enclosing Ellipsoid
３．学会等名 International Conference on Computer, Control and Robotics (ICCCR)（国際学会）
４．発表年 2021年

1．発表者名
Jian Liu, Yoji Yamada, Yasuhiro Akiyama, Shogo Okamoto, Yumena Iki

2．発表標題
A Novel Safety-Oriented Control Strategy for Manipulators Based on the Observation and Adjustment of the External Momentum

3．学会等名
International Conference on Computer, Control and Robotics (ICCCR)（国際学会）

4．発表年
2021年

1．発表者名
Hiroki Kito, Yoji Yamada, Jian Liu, Yasuhiro Akiyama, Shogo Okamoto

2．発表標題
Proposal of Fail-Safe Contact Motion Control and its Simulation using CRANE-X7

3．学会等名
2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR)（国際学会）

4．発表年
2021年

1．発表者名
Jian Liu, Yoji Yamada, Yasuhiro Akiyama

2．発表標題
Calculating the Supplied Energy for Physical Human-Robot Interaction

3．学会等名
2021 IEEE International Conference on Intelligence and Safety for Robotics (ISR)（国際学会）

4．発表年
2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

本研究の成果の一部である，軽傷レベルの重篤度を定量的に表現するための，単位面積当たりの力やエネルギー，さらには運動量を規範とする提案は，国際安全規格のISO/TR 21260に掲載をされることになった.

６．研究組織

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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関