別紙様式第１５号（論文内容の要旨及び論文審査の結果の要旨）

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論 文 内 容 の 要 旨

Non-physical interaction has been an interest in the control method in recent years. The conventional control methods that rely on hand and leg manipulation are incapable to be used for those who are physically disabled. Physically disabled people such as Amyotrophic lateral sclerosis (ALS) patients are paralyzed from neck to toe. They are constrained to do interaction by using their eye, mouth or head movement. Thus, we proposed using the bio-signals interaction method and we focus on the Electrooculography (EOG).

The research goal of this paper is to develop an EOG control method for robot operation. We have successfully enhanced the EOG measurement by increasing the signal measurement stability for the EOG gaze direction and improved EOG gaze estimation accuracy by proposing a calibration method. Other than that, we also able to determine which eye gaze methods; gaze direction or gaze estimation is the best for robot control operation.

In this research, the EOG eye gaze is discriminated into 3 types; gaze direction and gaze estimation, and eye blink. The gaze direction is successfully discriminated against to 8-directions by using maximum and minimum signal amplitude polarity. The gaze estimation is discriminated against by the computation of the signal integral. Inside the eye blink discrimination, there are two types of eye blink; voluntary and involuntary blink. The voluntary eye blinks can be discriminated by the value of the maximum and minimum amplitude value of the Ch2 signal. The amplitude has a higher value compared to other eye gazes. On the other hand, the involuntary blink is discriminated against by the Ch2 signal maximum and minimum amplitude time width. The involuntary blink is an instantaneous eye motion in nature, so the time width is significantly shorter compared to other eye gazes.

There are other methods implemented to support eye gaze EOG control. EMG bite is used to increase the eye gaze control inputs. The EMG bite is successfully discriminated by using the signal differential computation. The EMG produced a differential value higher than other eye gazes. Then, color-based image processing is used to assist the gaze estimation measurement. By computing a target object center point and compared with the gaze estimation, the object selection accuracy is improved.

There are three objectives in this research. For the first objective is to enhance the EOG measurement stability for eye gaze. A custom-made EOG mask is proposed. An investigation on EOG signal stability is conducted to compare the conventional manual hand electrode placement and the proposed method. Three times eye gaze directions (up, down, right, and left) are measured. The signal pattern, maximum amplitude consistency, and signal standard deviation are investigated. From the experiment, the proposed method has the best results. Thus, we understood that the signal for EOG mask is more stable.
The second objective is to enhance the accuracy of the EOG gaze estimation method using the calibration method. We proposed the conversion method for 24-point gazing data simultaneously and assumed a virtual origin (i.e., 25th point) on gaze coordinates with 24-point gazing data and applied an affine transformation to 24-point gazing data. Two sub experiments were conducted as a comparative investigation for the conventional and proposed methods. The first sub experiment was an accuracy investigation between the proposed method and conventional computation. The second sub experiment was to determine the accuracy of the proposed method using EOG gazing data. Both experiment results show that the proposed method has the best result. Thus, EOG gaze estimation accuracy is enhanced by the proposed method.

The final objective is to compare which EOG gaze method; EOG gaze direction or gaze estimation performs better for robot control. There are four sub experiments have been conducted. The first sub experiment is to investigate the accuracy of gaze estimation with the support of image processing. The image processing is used to determine an object center point and the accuracy is determined with the distance (error distance) between the gaze estimation and the object center point. The result shows that the error distances are in range of 1.5 to 3.0 [cm]. The distance then is used to create a circle area from the object center point. If the gaze estimation is in the area, the object is assume selected and the robot arm moved to the object center point position. The second sub experiment is to investigate gaze estimation method for object displacement task. Two error distances from previous result are used; 2 and 3[cm]. The two distances is investigated to determine if the control performance improved when the distance parameter changed. From the result, the 3[cm] error distances shows the best time for the object displacement task. The third sub experiment is to investigate the gaze direction method for object displacement task. Each eye gaze direction manipulate the direction of robot arm movement. There are two distances for robot arm movement; 2 and 3 [cm] proposed. Similar to gaze estimation method, the two distances is investigated to determine the control performance improved if the distance parameter changed. From the result, the 3[cm] robot movement shows the fastest time. The forth sub experiment is to compare the two gaze methods to determine which gaze method is the best for robot control. Using second and third sub experiment results, the gaze estimation shows the best result. Thus, the robot control for EOG is the best by using gaze estimation.

論文審査結果の要旨

本論文は，Electrooculography（EOG）を使用して３次元空間におけるロボット操作システムを開発したものである。 はじめに，視線の EOG 測定の精度の安定性を強化するために，3D スキャンを用いて 3D プリンターを用いたカスタムメイドの EOG センサマスクを提案している。 EOG 信号の安定性に関する計測実験により，従来の手動電極配置と提案方法を比較し，信号パターン，最大振幅の一貫性，および信号標準偏差を比較し，提案された方法は安定した測定精度を示している。次に新規キャリブレーション法を提案して EOG 視線推定法の精度を向上させることに成功している。 24 点注視データの変換方法を提案し，24 点注視データを含む注視座標の仮想原点（25 番目の点）を想定し，24 点注視データにアフィン変換を適用し，従来の方法と提案した方法の精度比較を行った。 比較実験結果は，提案された方法がよりよい視線推定精度結果を示している。また，EOG を用いた視線に基づくロボット操作には，自発的なまばたきによる EOG と口噛みしめによる筋電図（EMG）を用いたロボットグリッパの力制御が追加の操作法としてシステムに実装されている。ロボット位置の操作には視線方向と視線推定による２つを提案している。視線方向ベースのロボットの位置操作では、単一の眼球運動をロボットアームの先端を眼球運動の方向の方向に一致させるように操作している。視線推定に関しては，ロボットアームは眼の焦点位置の推定位置に従って移動させている。ただし，色ベースの画像処理を，視線推定位置のサポートとして，視線で指定した範囲内の把持対象物体の推定・識別に利用している。この方法には推定誤差（注視誤差）が存在し，画像処理を使用して対象物体の中心点を計算し，視線推定と比較することによって，このロボット操作法の精度を向上させている。ロボット操作実験結果に基づいて，視線位置の推定は、視線方向の方法と比較して，オブジェクトの移動に要する時間が短くなり，ロボット操作に必要な計算量が少なくなることを示しており，Electrooculography（EOG）を使用して３次元空間におけるロボット操作システムの開発に成功している。

これらの研究知見は，学術上および産業技術への社会貢献に寄与できるものと判断し，審査委員会において，上記審査論文に関する事項について詳細かつ厳正な審査を行い，審査委員会議の結果，博士(工学)の学位請求論文として価値ある業績と認め，よって本論文は博士（工学）の学術論文として価値のあるものと認める。

最終試験結果の要旨

学位論文を構成する学術論文として査読のあるジャーナルに２件，学位論文の基礎となる学術論文に関する判定基準「学術論文が査読付き学会誌や論文集（Proceedings も含む。）に最低２編掲載されていること」を満たしており，博士後期課程学生としての必要な単位も修得し，令和２年２月６日に学位論文の内容を中心として，またこれに関した事項について諮問を行った結果，応答も的確であり，合格と認めた。

発表論文（論文名、著者、掲載誌名、巻号、ページ）

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