論文の内容の要旨

論文題目　Registration and Deformation of 3D Shape Data through Parameterized Formulation
「パラメタ表現式に基づく三次元形状データの位置・形状合わせ」

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Recently, the research has been made progress on the accurate 3D shape restoration of objects in the real world into computer graphics. In this research, a laser range sensor is usually used to capture the 3D shape data of an object. However, the shape data is just partial in one measurement because of the view limitation of the sensor. In order to reconstruct the whole shape of the object, therefore, it is necessary to restore the neighboring status of partial data that can compose whole object shape. This restoration process is a registration among 3D data. Rough registration can be achieved manually by a user through Graphic User Interface (GUI). But, strictly speaking, it remains the gap between data, and the result is far from being accurate. Therefore, we need to develop an algorithm to automatically minimize the gap through quantative calculation.

The conventional registration algorithms are mostly concerned with the rigid-body transformation that determines the translation and rotation parameters between a pair of the corresponding 3D data. The algorithm solves the nonlinear equation to iteratively minimize the distance between a pair of corresponding 3D data with respect to the 6 unknown parameters (3 translation and 3 rotation parameters). This iterative minimization framework is widely known as Iterative Closest Point (ICP). The strategy of this framework can be categorized by four issues: registration ordering, matching unit, correspondence mapping, and error metric.

Registration ordering determines the correspondence timing of registration data. Sequential registration means that just one corresponding piece of data is considered for the registration data of interest, so it cause the local discrepancies because the registration error concerned with one pair of data is inherited and accumulated to the later registration pair. Simultaneous registration means all the corresponding pieces of data is considered, and therefore it can avoid the error accumulation, distributing them among all corresponding pieces. Matching unit determines the point sampling. All point matching uses all points of data. Feature point matching uses points satisfied with some condition, for example, high curvature points. Corresponding mapping determines how the correspondence is taken with respect to the points in the data. Error metric determines what kind of amount the error between the corresponding points is, namely, euclidian distance, color distance, and so on. To design the robust registration algorithm, we investigate the registration behavior in each issue. The result is that the simultaneous ordering, all point matching, closest point-to-point distance should be adopted for the robust registration.

The registration data usually includes the random measurement noise, which causes the wrong registration result. Hence we make effort to remove their effect. Our solution is to employ M-estimator according to the lorentz function. It can detect the outlier automatically, and align only the identical part of superimposing 3D shape data. To summarize the effectiveness of our proposed registration, we compare the registration result between ours and the conventional registration, and evaluate the estimation accuracy of registration parameter.

Our proposed registration has ever made a contribution especially to the preservation, analysis, and simulation of cultural heritage and assets to provide the archaeological knowledge.

As examples making full use of the merit of our robust simultaneous registration, we then show the shape comparison and analysis by superposing 3D data of ancient Chinese bronze mirrors, containing the decorated pattern, that have the sibling relationship. The mirrors were the offering from ancient China to Yamatai state. Yamatai state is the oldest state in Japan, but archaeologists still cannot specify its location, so this is one of the major controversies. It is said that Yamatai state distributed them to the local rulers, and that they made some replicas to distribute them to their followers again. The relationship among their mirrors is called "sibling relationship". To find the sibling relationship among mirrors, we need to pay attention to the cracks commonly inherited from the identical mold, and the spreading of cracks caused by the abrasion of the mold which is worn by continuous usage. Namely, sibling mirrors have the local shape difference. Our proposed registration can detect them accurately by regarding them as outliers. As an archaeological aim of this research, we can identify the manufacturing order among sibling mirrors, and then trace the distribution root back, and as a result, we may identify the location of Yamatai state.

Another example is the modeling of Fugoppe Cave and Ozuka Tumulus. Our simultaneous registration can align their whole shape data without local discrepancies. As our motivation of their modeling, we investigate how they were created. Fugoppe Cave and Ozuka Tumulus respectively has the carvings and paintings inside them, and archaeologists often ague over how ancient sculptors and painters created the carvings and paintings, since they usually imagine that it was dark inside them. The idea that ancient sculptors and painters used artificial light sources has been considered; however, this is generally suspicious since there is no firm evidence of that. In Fugoppe Cave, we consider that the natural light emitted by the sunlight could reach the interior of the cave. The reason is that the cave probably had the same entrance like the current entrance, which is large enough for the sunlight to pass through. Consider the Ozuka Tumulus that has mural using six pigments. If the tumulus was built with wall stones that were already decorated, we imagine that these stones were painted under the natural light of sunshine. But if the wall was decorated after it was built, we might suppose that the paintings were done under artificial light, such as light from taper. In the latter case, it is doubtful whether ancient artists could recognize their decoration by the taper light. Hence, we verify the possibility that they were decorated in the sunlight focusing on the shading and shadowing over the carvings and the color recognition of colors used for mural under sunlight or taper light.

Registration, including our proposed registration, is usually referred to as the rigid-body transformation. It can work just in completely the identical part. Hence, we consider the extended registration. Our extended framework enables the registration among 3D data that can deform each other through some known mathematical formula. For simple example, when comparing 3D data of two objects with the same shape but different size, we have to determine the scaling parameter in addition to the six translation and rotation parameters. It is also the case when aligning the data of a deformable object. When we replace a part of the range data, such as the cylinder, with a CAD primitive model in order to reduce the data amount or refine its shape, the parameter of the CAD primitive shape, the diameter and the height in cylinder case, should be determined from the measured data by fitting the primitive to the range data. In other words, these applications require determining more parameters concerned about shape parameter than just the 6 translation and rotation parameters, and our extended method can solve, in a unified manner, rigid-body transformation and shape parameter. In our framework, we assume that the shape changes are strictly defined by some parameterized formulation derived from the deformation mechanisms.

As this application, we estimate the shape parameter from the shape measurement data of mathematical plaster models made in Germany in the end of 19 century for educational purpose. They are a kind of cultural assets. Our motivation here was, due to no documentation about how to manufacture them, to identify the shape parameters when manufacturing their models, to estimate the deformation parameter by applying our extended registration framework to its range image and the data computed from the mathematical formula, in order to evaluate the manufacturing accuracy of the plaster model under the estimated parameter, and to remake the accurate model because the historian and the mathematicians are interested in the manufacturer's skill at those days. We actually estimate the shape parameter, and using them, we successfully reproduce the metallic mathematical replica model of the original plaster model with high accuracy. We evaluate the estimation accuracy of shape parameter.

Another application is to align the data obtained by the laser range sensor suspended beneath the balloon. We call this sensor floating laser range sensor, FLRS. In the present measurement system, a laser range sensor has to remain to be standing still on the tripod set up at the stable ground during a scanning. Since such fixed measurement takes much time and cost, we develop FLRS to provide the safer and more effective measurement of large object, such as cultural heritages. Different from the conventional 3D sensing system, this measurement result includes the distortion because of the movement during measurement, and we apply the extended registration to the distortion rectification, regarding the movement of FLRS during scanning as shape parameter. The proposed deformation registration pays attention to the significance of estimated parameter as well as the convergent registration result because the estimated parameter can be used for the system feedback. We also evaluate the estimation accuracy of FLRS movement, and the applicable limitation. We used this system for the modeling of Bayon Temple in Cambodia.

Finally, we summarize this thesis, with a conclusion, discussion and ideas about future work.