

Interactive Deformable Image Registration with Dual Cursor

Takeo Igarashi , Tsukasa Koike , and Taichi Kin 

The University of Tokyo

Abstract

Deformable image registration is the process of deforming a target image to match corresponding features of a reference image. Fully automatic registration remains difficult; thus, manual registration is dominant in practice. In manual registration, an expert user specifies a set of paired landmarks on the two images; subsequently, the system deforms the target image to match each landmark with its counterpart as a batch process. However, the deformation results are difficult for the user to predict, and moving the cursor back and forth between the two images is time-consuming. To improve the efficiency of this manual process, we propose an interactive method wherein the deformation results are continuously displayed as the user clicks and drags each landmark. Additionally, the system displays two cursors, one on the target image and the other on the reference image, to reduce the amount of mouse movement required. The results of a user study reveal that the proposed interactive method achieves higher accuracy and faster task completion compared to traditional batch landmark placement.

CCS Concepts

• **Human-centered computing** → **Human computer interaction**;

1. Introduction

Image registration (alignment) is the process of matching a target (moving) image to a reference (fixed) image [ZF03]. Rigid and deformable registration methods apply rigid and deformable transformations to the target image, respectively. Rigid registration is relatively easy to automate owing to the limited degrees of freedom involved (translation and rotation), whereas deformable registration is difficult to automate because it involves several degrees of freedom. Although numerous automated methods have been developed [SDP13], fully automated registration of images with very different appearances remains challenging.

Existing methods typically combine manual placement of landmarks with subsequent automatic deformation (interpolation). Herein, first, an expert user specifies a set of paired landmarks on the two images; subsequently, the system deforms the target image such that each landmark matches with its counterpart on the reference via a batch process. This approach is inefficient because the user must repeatedly move the cursor back and forth between the target and reference images. Moreover, the number of landmarks required to obtain a satisfactory result is difficult to determine.

To improve the efficiency of this manual process, we propose an interactive approach wherein the deformation results are continuously displayed as the user clicks and drags landmarks. This allows users to efficiently identify the optimal locations to place the next landmarks (i.e., the regions with the largest error) and to complete the process when the deformation results become satisfactory. To facilitate interaction, the system displays two cursors, one on the

target image and the other on the reference image, to reduce the amount of mouse movement required. The two cursors move synchronously following the mouse movement to obviate the need of moving the cursor back and forth between the two images.

We conducted a user study, wherein we compared our interactive method with a traditional batch-based baseline in the context of deformable medical image registration. Twelve neurosurgeons participated in the study. The results revealed that our method achieved significantly higher accuracy and slightly faster task completion compared to the baseline method. The participants' answers to a questionnaire indicated that our method was more intuitive, easier to use, and more efficient than the baseline.

The contributions of this study are summarized as follows.

- We proposed an interactive deformable image registration method with continuous feedback. Although interactive image "deformation" is widely used, the application of such methods to image registration has not been previously reported.
- We further proposed a dual-cursor interaction method to enable interactive deformable image registration. Multiple cursors have been used to browse registration results, but the present work is the first to apply this approach to interactively deform an image during registration.
- Additionally, we conducted an experimental evaluation to quantitatively demonstrate the effectiveness of the proposed interactive deformable image registration method; the evaluation was a user study conducted with neurosurgeons as participants.

2. Background

In this study, we predominantly consider medical image registration methods. Unimodal registration matches images captured using the same imaging system (e.g. CT-to-CT), whereas multimodal registration matches images captured using different imaging systems (e.g. CT-to-photograph). Multimodal registration is particularly difficult to automate because images of different modalities differ considerably. Hence, partially automated methods remain dominant in practice.

In particular, this work was motivated by the task of multimodal registration between a photograph of the surface of the brain during surgery and a 3D rendered view reconstructed from a brain scan. The photograph is deformed to match the 3D reconstruction. This registration process is important for neurosurgeons to map information, such as the locations of hidden blood vessels, shown in the 3D scan to the real view of the surface of the brain during surgery. However, this task is difficult to automate because the photographs and scanned images differ considerably; not all arteries are reconstructed. Moreover, the shape of the brain varies significantly from the scan because of brain shift, which is caused by the inflation of the brain as soft material when neurosurgeons cut open the skull [GKOP*17].

"Interactive" image registration methods have been proposed in previous works [Wu14,LWRS09,KKT*21b]. However, this refers to the process wherein a user manually places landmarks on the two images using a graphical user interface; the subsequent deformation was performed as a batch process. Prior works on medical imaging have focused on deformation algorithms [SDP13], and research on user interfaces for such applications remains limited.

Multiple cursors have been used in medical imaging to indicate common locations in multiple images [PDHF07, LG03, RKU*96], and are referred to as dual, joint, or linked cursors. The key difference between the existing and proposed methods is that existing methods use multiple cursors only to *browse* static images, whereas the proposed method uses multiple cursors to *deform* a single image to match with the other. Multiple cursors have also been used to reach distant targets on a large screen [KI08]. Furthermore, this work was inspired by studies that interactively adjusted a mapping between a mouse and a cursor [BGBL04, LBE04, FLTL08].

3. Dual Cursor Interaction

First, we describe the baseline batch-based method (Figure 1). We implemented this baseline as a representative method adopted in the literature and commercial products. The system shows the target and reference images on the left and right, respectively. The user specifies pairs of landmarks on the two images one at a time, and a single cursor is displayed. The user first specifies a landmark on one image by clicking (Figure 1a) and then moves the cursor to the other image to specify the corresponding landmark with another click (Figure 1c). Thus, a click-(long)move-click interaction without continuous feedback specifies a pair. The images are static and no deformation is applied during the placement. After the user specifies all the landmarks, the system applies deformation as a batch process (Figure 1d).

Next, we describe our proposed method (Figure 2). The system

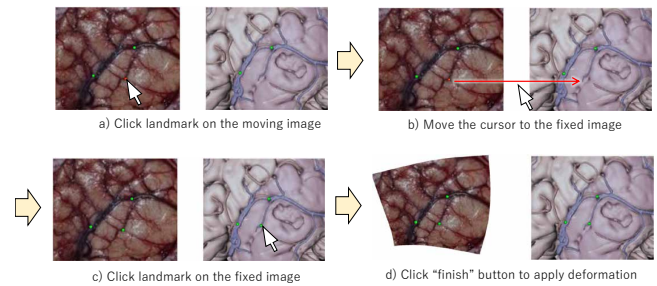


Figure 1: Traditional batch registration with a single cursor. The user specifies landmarks on both images by clicking (top). The system deforms the target image only after all landmarks are specified (bottom).

shows the target image on the left and reference image on the right. As the user moves the primary mouse cursor over the target image, a secondary cursor appears at the corresponding position on the reference image. In particular,

$$p(\text{secondary cursor}) = p(\text{primary cursor}) + \text{offset} \quad (1)$$

$$\text{offset} = p(\text{reference image}) - p(\text{input image}) \quad (2)$$

where $p(x)$ represents the screen position of x . Suppose the user aims to associate a landmark at position p_0 in the target image to a corresponding landmark at position p_1 in the reference image. The user first moves the primary cursor to position p_0 (Figure 2a). Subsequently, they click at that position, and a pin then appears under the primary cursor. Simultaneously, another pin appears under the secondary cursor (Figure 2b). The user then drags the secondary cursor to position p_1 with the mouse button down. The target image is continuously deformed as the user drags the cursors (Figure 2c). The user releases the mouse button to finalize the placement (Figure 2d). To summarize, a click-(short)drag-click interaction event with continuous feedback specifies a pair. The user repeats the process as necessary to specify a sufficient number of landmarks. When necessary, the user can drag the existing pins to adjust their position. Optionally, the user can press the shift key to tentatively place a translucent version of the reference image over the target image to visualize the match between the two.

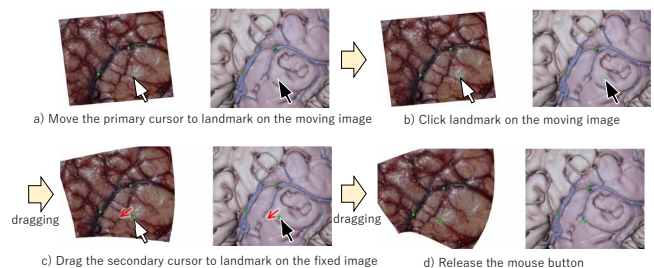


Figure 2: Interactive registration with dual cursors. The user grabs a landmark on the target image (top) and drags it to corresponding position on the reference image (bottom)

4. Implementation

We implemented the prototype system using the Unity engine, and tested it on a Windows PC. Although the current implementation uses a mesh-based deformation algorithm [IMH05], any deformation algorithm suitable for a given task, such as traditional thin spline interpolation [TO02] and more advanced space deformation techniques [JBPS11, SMW06], can be used. We used Math.NET Numerics[†] as a sparse matrix solver.

5. User Study

We compared our method with a traditional batch-based baseline method on the task of multimodal deformable registration between a photograph of the surface of a brain and a rendered 3D brain surface reconstructed from a scan. Figure 3 shows an example. The user deforms the photograph (left) to match with the rendered image (right).

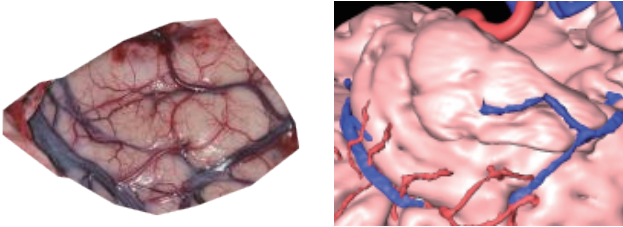


Figure 3: Task example.

5.1. Procedure

We recruited twelve participants (one of whom was female, others male) between the age 29 and 46, all of whom were neurosurgeons who were familiar with the task of viewing the surface of the brain during surgery. We used a within-subject design. Each participant completed three registration tasks consecutively using one method, and then completed the same three registration tasks using the other method. Six participants used the proposed method first, and the other six used the baseline method first. We prepared six registration tasks (image pairs), and each participant worked on the six tasks in a random order. Each participant did not work on a given image pair more than once to avoid any effects from learning specific images. Each participant completed a tutorial and a practice session before using each method and provided their responses to a questionnaire after completing all six tasks. We asked each participant to place a fixed number of landmarks (25). We measured the time required to complete the task as well as the total distance that the users moved the mouse during the task and accuracy of the results. The questionnaire asked each participant to directly compare the two methods on a scale of 1 to 5 (3 being a neutral score) in terms of *accuracy*, *predictability*, *intuitiveness*, *efficiency*, *fatigue*, *confidence*, and *easiness*.

Evaluating accuracy is not trivial because no data are available that can be considered as ground truth. Hence, we recruited two

neurosurgeons who did not participate in the study to quantitatively evaluate the accuracy of the participants' work. They measured target registration error (TRE) as follows. First, they evenly divided the reference image into a 4×4 grid (Figure 4). In each grid cell, they measured the largest deviation of a vessel center between the deformed image and the reference image together. They ignored the cells that presented difficulty in measuring such deviation. Finally, they took an average of the measurements in the grid cells. Similar methods have been used to measure registration errors [FW01, Fit09, YSK*15, KKT*21a, MMF98].

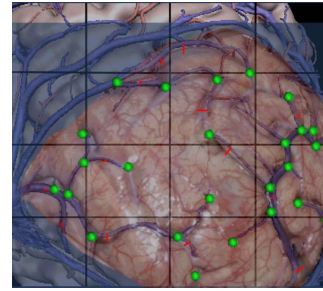


Figure 4: Evaluation of target registration error (TRE). The red lines shows the largest deviations in each grid cell.

We used linear mixed model [LW82] to statistically test TRE, required time, and the amount of total cursor movement. For the questionnaire, we used a one-sample t-test at a two-side significance level of 0.05 against the null hypothesis that the change from baseline was 3 (neutral) for each question in the questionnaire [Stu08]. We used the JMP Pro 15 data analysis software (SAS Institute Inc, Cary, North, Carolina) to perform these calculations.

5.2. Results

The TRE of the proposed method was $1.07 \pm 0.05\text{mm}$ (mean \pm standard error), whereas that of the conventional method was $1.25 \pm 0.05\text{mm}$ (Figure 5 left). The proposed method exhibited significantly higher registration accuracy ($p = 0.0057$). The average task completion time was 271.5 s for the proposed method and 277.3 s for the conventional method (Figure 5 right). Thus, the proposed method was slightly faster, but the difference was not statistically significant ($p = 0.7957$). The average amount of cursor movement was 22,654 pixels for the proposed method and 57,001 pixels for the conventional method. The difference was significant ($p < .0001$).

To check the assumptions of the linear mixed model, we calculated estimates of variance components using the REML method to check the normality of the residuals. The normality of the residuals was confirmed using the predicted value-residual plot. The TRE exhibited a positive deviation from the normality assumption. This was most likely the case because TRE considers only positive values. After log conversion ($\log(1 + TRE)$), we repeated the same analysis, and found that the trend of the results did not change. Moreover, we obtained a plot that seemed to satisfy the assumption of normality. Therefore, although the main results do not necessarily fit the model well, the results appear to be robust to the model's assumptions.

[†] <https://numerics.mathdotnet.com/>

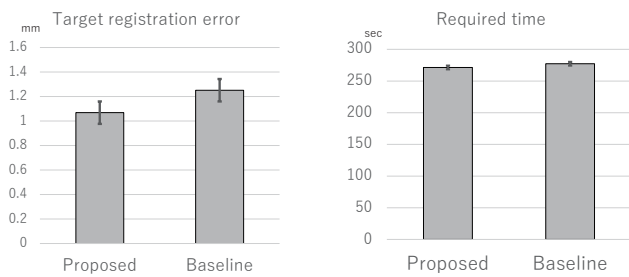


Figure 5: Target registration error (left) and task completion time (right).

The results of the questionnaire are shown in Figure 6. The proposed method was significantly more applicable to the item more accurate, with an average score of 3.6 ($p = 0.0463$), and to the item more predictable, with an average score of 4.4 ($p < .0001$). Although the other items more intuitive, more efficient, less fatigue, more confident, and easier to use all had mean scores of three or higher, the difference was not significant.

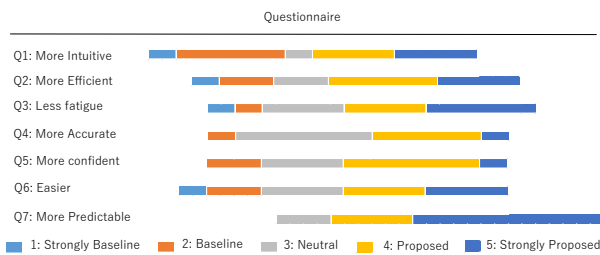


Figure 6: Questionnaire Results.

5.3. Discussion

The proposed method achieved a higher accuracy in terms of TRE. The participants answered that was the case because the proposed method allows the user to monitor the progress of the deformation while placing the pins. The participants were able to efficiently determine the areas that needed more pins, which is difficult without constant feedback. Although an improvement of 0.17 mm (14% improvement) might seem too small to be relevant, our study participants confirmed that this was a meaningful improvement because the size of minute vessels are in the order of 0.1-0.5 mm.

Although the proposed method did reduce the time required to perform cursor movement, the participants required a relatively long time to find corresponding anatomical structures because their locations moved on the screen during the participants' placement of the first few pins owing to the large initial deformation of the image. The speed of the process subsequently increased with the number of pins positioned. The participants provided similar descriptions as free comments in their responses to the questionnaire. In contrast, with the conventional method, the deformation is performed after landmark placement; thus, it continued at a regular

pace until the task was completed because the location of the corresponding anatomical structures in the deformation image did not move on the screen.

Regarding the total amount of cursor movement, the conventional method required participants to move the cursor back and forth between target and reference images repeatedly. In contrast, in the proposed method, participants did not need to move the cursor back and forth, and the amount of cursor movement tended to decrease in the latter half of the work because of real-time deformation. This is the reason that the amount of cursor movement required to complete the task was reduced.

The questionnaire results on the items accuracy and predictability seem to reflect the results of the TRE. The results on intuitiveness, effectiveness, confidence, and ease of use match with the free comments provided by the participants; for example, they noted that familiarizing themselves with the behavior of the proposed method when placing the first few pins took some time. In regard to the item fatigue, the participants commented that finding anatomical structures other than blood vessels was difficult in both methods, which explains why no significant difference was observed.

6. Conclusion

In this study, we proposed an interactive landmark placement method for deformable image registration, wherein the target image is continuously deformed in real time as the user places landmarks on the images. Furthermore, we presented a dual-cursor interaction to enable such interactive deformation. We conducted a user study on multimodal medical image registration with twelve professional neurosurgeons, and the results revealed that our proposed method is more accurate, slightly faster, and requires less mouse movement compared with the conventional approach.

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