Chapter 4

Composition and registration of 3–D ecographies

This chapter is concerned with the registration of medical images of the same patient from ultrasound to MR images. During a neurosurgery intervention, MR images are often employed as a guide despite the fact that they do not show the actual state of the brain, which sometimes has sunk up to 1 cm. By means of a standard ecographer and a tracker connected to a computer, it is feasible to build on-line a more recent picture of the brain. After registration with the previous MR image, the surgeon is provided with a more accurate guide. For the purpose of automatic registration, we employ the cortical folds as anatomical landmarks. The whole process is made fully automatic: the segmentation is performed by a the creaseness operator, and the later registration follows a fashion similar to that of previous chapters.

During the last 5 years many new applications based on ultrasound ecography (*us*) have arisen. The technical improvements they were based upon are not any major changes in the device itself, but the possibility to locate spatially the *us* probe within an external coordinates system. Since each acquisition frame is located in a precise manner, the information contained in one frame can be combined with that of the previous to produce a volume image, or perhaps registered and fused with other image modalities.

I started working in this subject under the supervision of Dr. D. Hill, during a stage at the CISG, Guy's Hospital Campus , London, which lasted from January to August 1999. The hosting group had little experience in this particular subject, but wide knowledge in related medical areas and excellent medical facilities, which made nice and feasible the arduous aim. When the stage was over, we had successfully covered most steps and we were able to compound a volume *us* image. Unfortunately, the final aim, fusion and registration in a real neurosurgery case, could be only partially achieved due to the lack of time.

Upon my return, we invested many efforts in replicating the system which had already worked at CISG. Most inconveniences were due to the physical distance be-

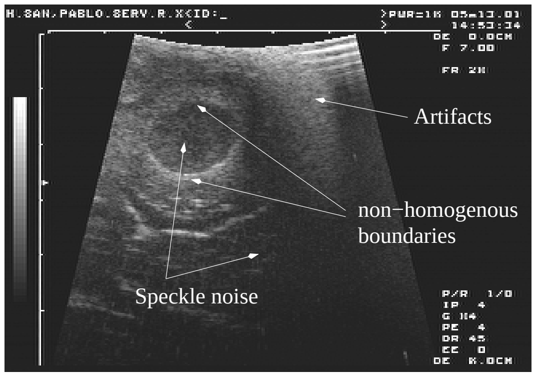

Figure 4.1: Ecographies' poor image quality make automatic processing difficult.

tween us and our medical partner, the Hospital de la Santa Creu i de Sant Pau. In effect, we could not carry heavy equipments such as those used in the first project, a Sun workstation and an optical tracking device. Another trade-off were the limited computer facilities.

Therefore, another system, fully portable, had to be built and, since hardware components and operating system were different, most of the software had to be re-written. Although the prototype worked well after some adjustments, the final fusion with the MR image could not be achieved simply because the MR device in Sant Pau did not provide any means of digital transfer. In addition, the intraoperative equipment was somewhat too sensitive and very often it simply stopped working.

As a result, most work in the final stage, namely, the 3D *us* to MR registration, had to be done in a second stage at the CISG. During it, which lasted for 10 days, we adjusted the settings to achieve a proper calibration, and after, since no intervention was due to happen, instead we performed some experiments with an in vitro human brain.

The chapter is organised as following: first, we emphasise the potentials benefits of ultrasound registration and fusion. Next, we briefly describe the components that the system must have, and a history of the contributions from different groups to this subject. The following sections are devoted to our research, comprising the full specifications of our system, some mathematical problems that arise and the live ecography compounding. Finally, we demonstrate the performance of the same algorithm presented in previous chapters for the 2D–3D and 3D–3D registration of ecographies and MR volume images.

4.1 Ecography for diagnosis

Ultrasound ecography is a popular imaging technique because:

- images are immediately available.

- it is radiation-free, so any number of scannings may be made to any area, including foetus.
- the acquisition device is relatively inexpensive and fairly transportable.

The imaging procedure requires the ecography probe to be in physical contact with the surface of the object to be imaged. While the radiologist manipulates the probe along the surface (free-hand scanning), the image displayed in a monitor changes dynamically and she is able to reconstruct mentally the structure underneath the skin. Hard copies of interesting images (individual video frames are called B-scans) are available for a further analysis and measurements.

Figure 4.3 shows four frames from a typical ecography video sequence. At the sight of these images, it can be understood that interpretation and diagnosis require good skills from the operator. Compared to standard CT or MR image volumes, the slices have not been taken in a regular fashion, therefore mentally fusing a real-time stream of hundreds of B-scans is not a trivial task.

Ecographic images are very useful because it is a real-time modality: the clinician is able to see immediately the region to be explored. But, because of the way images are acquired, their quality is poor compared to other modalities. Note, from figure 4.1, that ecographies:

- suffer high speckle noise interferences
- present high-contrast artifacts, not distinguishable from actual contents
- boundaries are not homogeneous along the image
- secondary reflections of the signal cause artifacts mirroring real features
- the signal may not be strong enough to reach and come back from all the regions in field of view, thus leaving wide void or low-contrasted areas.

Many other sources of errors exist; they have been classified into several groups: propagation and attenuation artifacts, position measurement errors and tissue-related errors. See [84] for an exhaustive list.

3–D ultrasound represents an improvement to the traditional viewing procedure. In this modality, all the information is located accurately in a cubical voxel array, so accurate volume or distance measurements are possible, and also many of the image processing techniques already available for conventional radiologic images.

But full 3–D snapshots acquisition is still not technically possible. One approach consists of attaching rigidly the probe to a mechanically driven reference. Then the resulting sequence of B-scans sample the anatomy in a regular known spacing, and they can be placed in an array fashion to produce a volume presentation. This approach, however, needs the region to examine to be of a regular shape, otherwise the transducer would lose contact and the signal would be lost.

Many similar approaches exist. For instance, the so-called intra-vascular ultrasound, IVUS. In this modality, the miniaturised transducer is placed within a coronary artery and is rotated and translated with a known speed to generate cross sectional images. In this case, the volume presentation is built in a polar coordinate system.

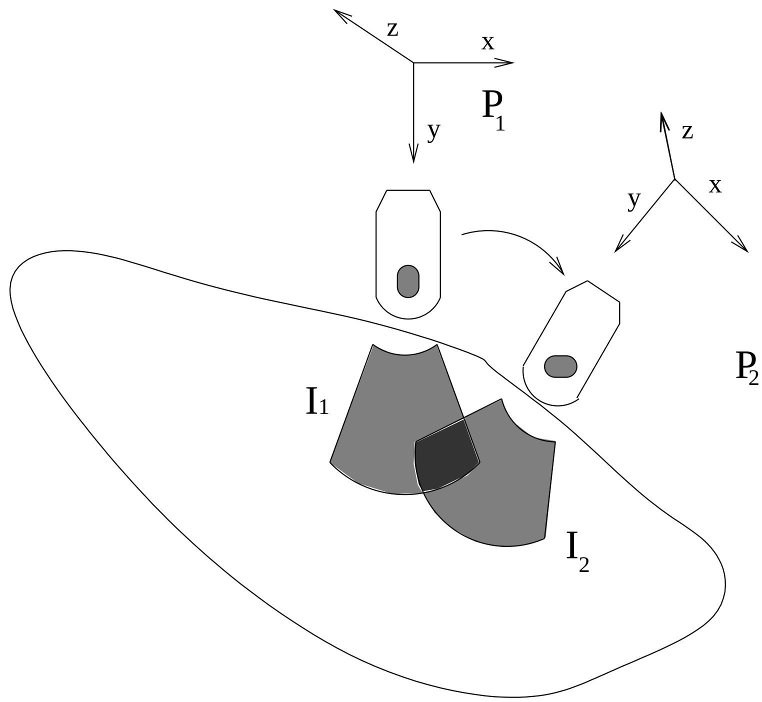

Figure 4.2: Each b-scan I_i is related to a position P_i in some external coordinate system

Yet, these systems can not be applied to generic patient examinations because the physician needs to scan in an unrestricted fashion, and the contact surface may take any geometry. The free-hand paradigm proposes to track the position of the transducer during the examination, so each b-scan has known position and orientation (figure 4.2). With this information, the image contents have known spatial location respect some external reference system and can be combined to produce a single volume image.

This chapter will focus on the free-hand paradigm for 3-D ultrasound composition.

4.2 A system for free-hand ecography

In the last section we introduced the ecography as a medical tool for diagnosis, and briefly described a system, the free-hand ecography which would widen the scopes of the clinician. In this section we give a detailed description of its general components, in order to set the background for the following sections.

A free hand system must be able to track the position of the transducer, grab the image acquired at that particular moment and then combine all the information. It consists of the following elements:

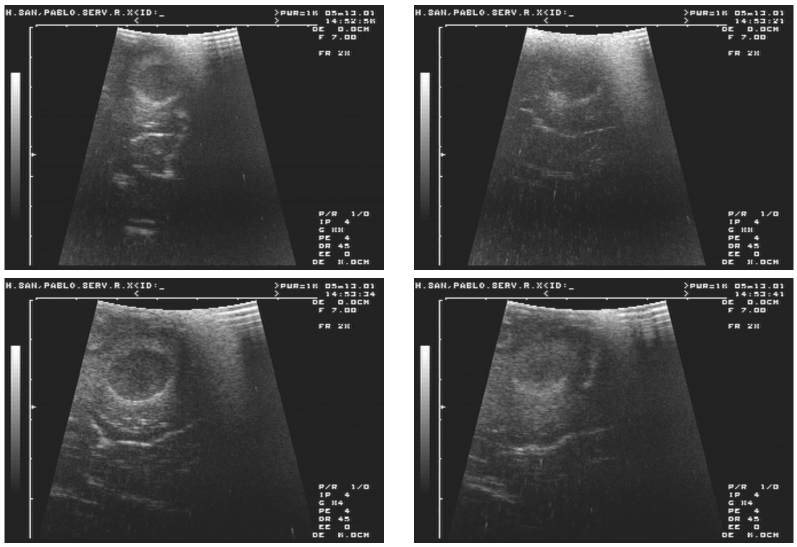

Figure 4.3: Samples from an *us* sequence

- an ultrasound ecographer with (ideally digital) video output.
- a 3-D tracker to track the ultrasound transducer as accurately as possible.
- a computer, with two inputs: the ultrasound signal and the tracker position. It must be able to store in real time all the incoming information. The slowest of the these elements determines the final rate in frames per second of the system.

These elements are depicted schematically in figure 4.4. The tracking system shown needs some further explanation. There exist three types of tracking devices: electromagnetic, optical and mechanical. The electromagnetic system is compounded by two elements: the emitter, which emits a strong magnetic field, and the receiver, which is able to read the intensity and direction of the field. Both elements are controlled by a central process unit, which is responsible of computing the position of the receiver respect to the emitter, and send the data to the computer. This is the type shown in the figure (Minibird is the trade mark of the system).

The optical system is based on the readings of two or three cameras rigidly mounted on some stable structure. The central processing unit searches in the images given by each camera a particular landmark or light emitters and then, by means of triangulations, is able to estimate their position. The landmarks need to be rigidly attached to the object to track and they must be in sight of the cameras. For the passive case, some designed pattern or figure is used, while, for the active, a set of diodes.

Still, there is a third type, the mechanical-based tracking, where the transducer is attached rigidly to a set of mechanically-driven arms able to measure the movements

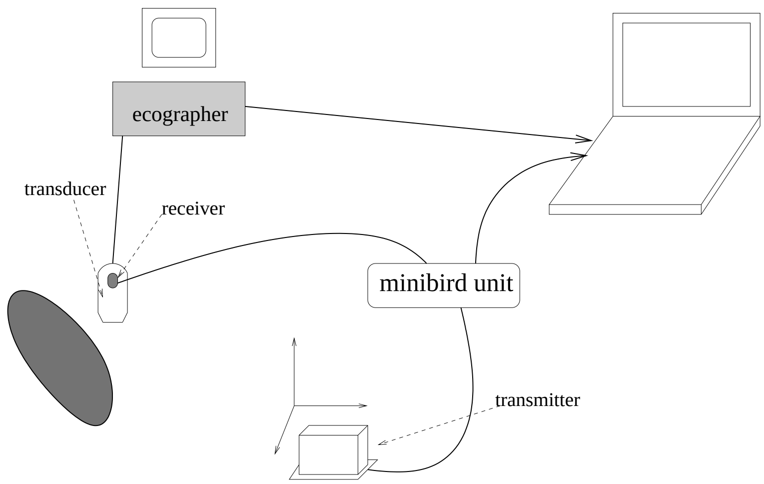

Figure 4.4: Elements of a free-hand ecography system.

made in the tracker. This type is of little use in free-hand ecography because of the poor freedom of movements it provides to the surgeon.

C.S.	Abbreviation	Origin	Units
Ultrasound	**U**	Top left corner of image	Pixels
Receiver	**R**	Some point near the transducer	mm
Transmitter	**T**	The transmitter unit	mm
Cuberille	**C**	Some arbitrary point by the scanned object	pixels

Table 4.1: Coordinate systems involved in the composition

The operation of placing each pixel from the ecography to the final world coordinates is described by means of transformation matrices. The coordinates systems are defined in table 4.1.

A pixel with coordinates (x, y) in **U** will be transformed to other coordinates (x', y', z'), and the equation relating them is [85]:

$$(x', y', z') = (x, y) \cdot M_U^R \cdot M_R^T \cdot M_T^C \tag{4.1}$$

, where M_i^j stands for the transformation matrix from i to j.

M_U^R , so-called calibration matrix, includes the scaling parameters and the position of the top left corner of the image with regard to the centre of the receiver. Its values are constant provided the receiver's position on the transducer is kept stable and the ecography settings are not changed.

Since the scaling and position parameters are unknown, they must be estimated. Although some papers simply measure the distance between the receiver and the tip of the ecographer, it is much more reliable and precise to calculate them statistically

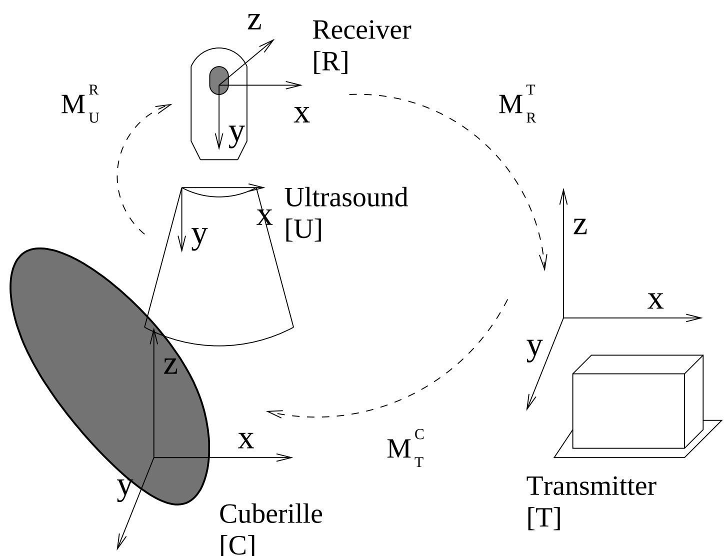

Figure 4.5: Coordinates systems involved in the free-hand ultrasounding

by scanning some object with known shape and size. This is known as calibration, and will be described in detail in section 4.4.2.

M_R^T contains the position and orientation of the receiver with respect to the transmitter. Therefore, the values will change as the clinician moves the transducer where the receiver is attached. M_R^T inevitably contains positioning errors, caused by interferences and the limited accuracy of the tracking device.

M_T^C is used for the sake of a proper location, orientation and scaling of the array of voxel system coordinates. After applying M_R^T in equation 4.1, the resulting coordinates will likely be some distance away from the coordinate origin, and also the distance between pixels will be set by the tracker specifications.

But in general this will not be adequate; probably, the area to be scanned is rather small compared to the whole volume needed, so we would like to take into account only those coordinates near the scanning. Therefore, M_T^C will be chosen at user's will, in order to contain the area scanned and with a given scaling and orientation.

Once the system has been calibrated, i.e., M_U^R is known, the information (image, position) can be used in many ways. Perhaps the most obvious is to compound a volume image, but others exist. Gee, for instance, in [19] describes a method to resample the data on a curved, not flat, surface, without actually producing the intermediate image. In the next section we review the main papers in the field. We remark both the calibration process and the final application, since both are critical for the final success.