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Manual control of patient table for bolus-chasing CT angiography

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Abstract. In order to reduce contrast dose and radiation exposure involved in CT angiography, an automatic adaptive control scheme was proposed for bolus chasing, which offers substantial improvements over the conventional constant speed control scheme. In this paper, a manual control scheme is proposed to utilize the expert's knowledge optimally based on real-time imaging feedback. The technical objective is to synchronize the bolus dynamics and the imaging aperture. To test the proposed technique, a realistic simulator is designed, developed and evaluated. It is shown statistically that the manual control outperforms the traditional constant speed control.

Keywords: CT angiography, simulator, manual control

1. Introduction

The CT technology has advanced greatly since the invention of the first protocol. However, the table control strategy has not evolved beyond the simple constant speed scheme. In a typical CT scan, the arrival of the bolus triggers a constant movement of the patient table [1,2]. The problem with this method is that the contrast bolus does not travel at a constant speed. Given a small aperture of the scanning region, the bolus peak might not be in the field of view, or may even move out of the field of view after the first few seconds of the scan, which results in poor image quality. Efforts have been made to develop a so-called adaptive bolus chasing CT angiography that estimates and predicts the movement of the bolus peak in real-time and then moves the patient table according to the control laws developed [3–6] so that the bolus peak and the imaging aperture can be synchronized. The advantages of the adaptive scheme have been demonstrated theoretically and experimentally in [3–6].

In this paper, a manual control scheme for CT table movement is proposed. The idea is that given a real-time CT image display, an operator is able to control the patient table according to real-time local bolus information. It is expected that with some training, a manual control based process would outperform the

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Fig. 1. Illustration of CT table simulator. which is compose of joystick and laptop.

constant speed control [7,8] process, and is more or less the same as the adaptive control in most cases. In some complicated cases, a manual control could even outperform both the constant speed control and the adaptive control. To test this hypothesis, a realistic bolus chasing simulator is developed to study constant speed control, adaptive control and manual control schema using clinical data. Furthermore, operators including experienced interventional radiologists and those with little medical training are recruited to perform the manual control for comparisons. Finally, hypothesis-driven experiments are conducted and analyzed via the t-tests [9]. In the following, we will describe the simulator, experimental designs and statistical results to quantify the performance of manual and constant controls.

2. Methods and material

2.1. Simulator functionalities

The major function of the simulator is to simulate a CT angiography process realistically and interactively (Fig. 1). The simulator provides three control options for CT table, adaptively which is completely automatic, manually by an operator using a joystick or at a constant speed, respectively. The software determines whether the CT gantry aperture is within or outside an acceptable zone. The acceptable zone is defined as where the bolus density is higher than the operator-prescribed percentage of the peak bolus density. In practice, the image quality within this zone is considered adequate. The error of the table control is the distance between the closest acceptable zone boundary and the imaging aperture. After the data is collected, one can press a button to analyze the data statistically. The software assumes that 512 pixels on the screen cover 1.5 meter. The animation is played at 30 frames per second.

2.2. Software design

The interface of CT Table Simulator shown in Fig. 2 consists of four major components: The Control Frontend, the Simulator and Display Frontend, the Communication Backend, and the Data Analysis Backend (Fig. 3). A CT cine is displayed in real-time during the simulation, which provides feedback to the operator for manual control. The image can be zoomed into any region at the operator's choice as shown in Fig. 4.

The Control Frontend, as the name implies, consists of controls for the user to modify the parameters of the CT Simulation. The control interface is divided into three major parts: Bolus and Table Parameters,

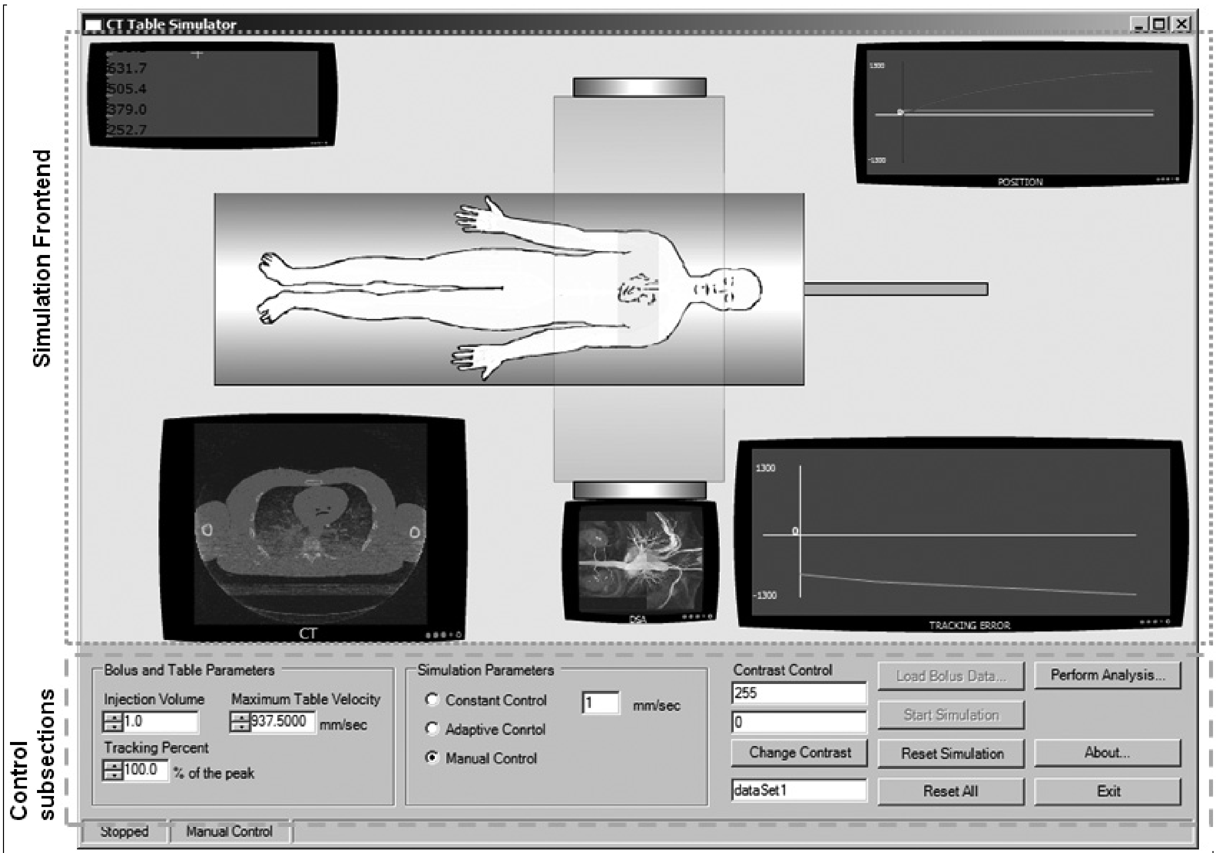

Fig. 2. The interface of our simulator. The three control subsections are seen on the bottom, and "zooming" contorls are seen on the right. The simulation fronten dis seen above the controls in a large screen. Information presented in the simulation frontend can be used as feedback for the operator.

Simulation Parameters, and Program Control Buttons. The Bolus and Table Parameters specify the Bolus Injection Volume, Maximum Table Velocity, and Tracking Percent which quantifies the relative deviation from the bolus peak. The Simulation Parameters allow the CT Table to be simulated with a Constant, Adaptive, or Manual control. Each of these controls will be explained in the next section.

The Communication Backend is a Communication Abstraction Layer between the two Frontends, and the Data Analysis Backend. This Abstraction Layer enables the software to be deployed on different platforms, such as in a web application or under different platforms including Linux. The user can control the parameters of the simulation through the Control Frontend. The parameters are encapsulated and sent through the Communication Backend and to the Simulator and Display Frontend. Data is collected in the Simulator Frontend, encapsulated, and sent through the Communication Backend to the Data Analysis Backend.

The Data Analysis Backend analyzes the data statistically for each of the control modes. When the experiments are finished, all the data are saved and presented as shown in Fig. 5 after clicking the Performance Analysis button. The simulation of the CT scanner is done in the Simulator Backend. The Simulator Backend is directly coupled to the Simulator Frontend, meaning that they act as one entity. The interaction between different components is also shown in Fig. 5.

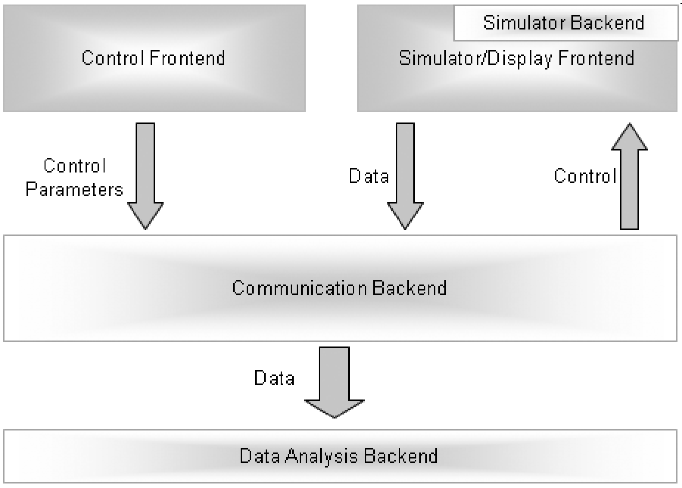

Fig. 3. Flowch art of the Software Design. The communication backend acts as an abstract layer for the frontends, and data analysis backend.

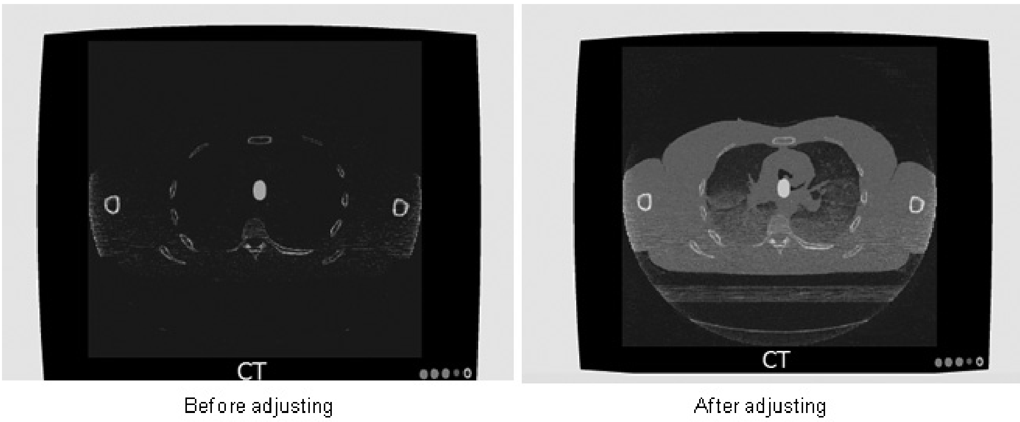

Fig. 4. A real-time CT imaging window that can be zoomed into any region by adjusting display window.

2.3. Table movement simulation

The controls, excluding buttons, are split into the two groups: Bolus and Table Parameters, and Simulation Parameters. The Bolus and Table Parameters enable the user to define the Injection Volume of the bolus (Multiplier), the Maximum Table Velocity (mm/sec) and the Tracking Percent (% of the peak). The Injection Volume controls the injection volume of the bolus. The length of the bolus is expressed as $L = a \times d$, where L is the length of the bolus in pixels, a is an Injection Volume constant, and d is the distance the bolus traveled relative to its starting position. The Maximum Table Velocity controls the maximum velocity of the CT Table. The Tracking Percent specifies a range of values within which the error is considered to be 0. The Tracking Percent is defined to be the relative peak bolus density.

Table 1
Summary of clincial bolus propagation datasets, where M/F is for Male/Female, Wt for White, AA for African Amreican, Hs for Hispanic, Un for Unknown Race, St for Stricture, Ath for Atherosclerosis, Em for Embloism, Th for Thrombosis, AAA for Abdominal Aortic Aneurysm, and DM I/II for Diabetes Mellitus I/II

Disease category	Patient information	Body site	Bolus speed (cm/s)	Mean speed (cm/s)	ECG-Gated delay
Occlusive-stemosis	M/Wt/69; St	Femoral	14–23	10	5/10
	M/Wt/49; Ath	Illiac	10	3.2	2/10
		Demoral	16	5	2/10
	F/AA/56; Ath. St	Illiac	10	5	5/10
	F/Un/55; Ath	Illiac	10	5	3/10
	M/Wt/77; Ath, St	Illiac	8–10	6	2/10
	F/Wt/80; Ath, St	Femoral	8–10	3	2/10
Occlusive-Blockage	F/Wt/62; Em & Th, St	Illiac	15–20	10	2/10
	M/Wt/63; Em & Th	Illiac	9	5	2/10
Aneurismal	M/Wt/70; AAA. DM II	Ab Aorta	8–13	3	2/10
		Illiac	10	2.7	3/10
	M/Wt/79; AAA	Illiac	21	7	3/10
	M/Wt/80; AAA, EM & Th	Ab Aorta	19	2	2/10
		Illiac	11–16	5	5/10
	M/Wt/49; AAA	Ab Aorta	17–22	4	1/10
		Alliac	9–21	4	2/10
Micro-vascular/Sub-Angiographic	M/Wt/88; DM II, St. Ath	Illiac	9–11	4	2/10
	M/Wt/77; DM II, Ath	Femoral	12–15	10	9/10
		Popliteal	10	7	1
		Popliteal	21	12	1
	F/Wt/35; DM I, Em & Th	Ab Aorta	31–38	16	1/10
		Femoral	15–17	11	2/10
	F/Hs/55; DM II Ath	Illiac	13–17	5	2/10
	F/Hs/55; DM I, Em & Th, Ath	Femoral	16	6	3/10
	M/Wt/77; DM II, Ath	Femoral	13–14	6	2/10
		Popliteal	18–21	6	3/10
	M/Wt/52; DM II, Ath	Popliteal	10–14	7	1

2.4. Software implementation

The CT Table Simulator is written in Microsoft C# .NET 1.1 and Macromedia Flash 8.0 [10]. Flash 8.0 is a popular developmental tool capable of creating interactive animations with the help of its scripting engine Macromedia Flashscript 8.0. The build in interoperability between Flash and C# makes the implementation of the Communication Backend straightforward. The Control Frontend, the Communication backend and the Data Analysis Backend are all written in C# while the Display and Simulation Frontend is created in Flash 8.0 and written in Flashscript 8.0. Communication between the Control Frontend and the Communication Backend is readily supported, because talking between the Communication Backend and Flash 8.0 is relatively trivial. The Joystick Control is part of the Control Frontend. Joystick Implementation is done with the help of Microsoft DirectX 9.0c DirectInput. The joystick is polled every 30 milliseconds on a dedicated thread in the software. During this slice of time, the proportion of the joystick's maximum tilt is calculated, and a multiplier is applied to determine the difference in pixels the table will move. Essentially, the joystick controls the velocity of the table.

2.5. Bolus datasets

A number of bolus datasets were stored in the local disk. The Simulator can load any one of them. These are real clinical data collected by our medical collaborators. For instance, the datasets from [3]

Table 2
Experimental data

	Error (mm)
Constant speed control	186
Manual control (interventional radiologist)	
Trial 1	59
Trial 2	87
Trial 3	84
Trial 4	52
Trial 5	50
Manual control (no medical training)	
Trial 1	88
Trial 2	69
Trial 3	91
Trial 4	65
Trial 5	49

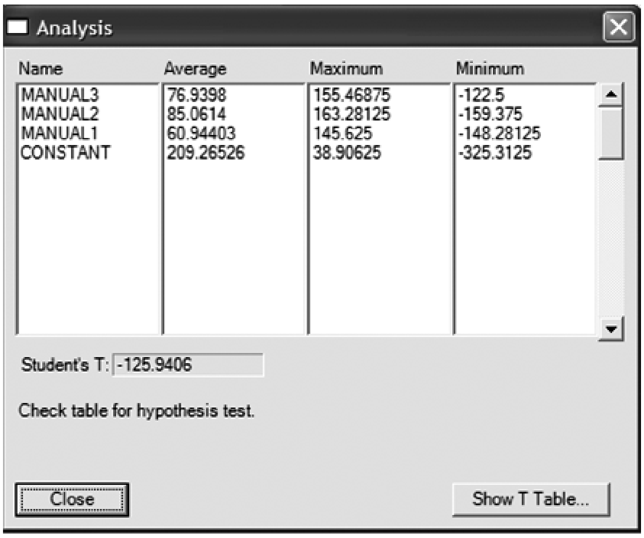

Fig. 5. Respresentative simulation experiment, where an operator performed 3 trial runs. A run assuming a constant table speed was also done. The student'st value is shown to test the hypothesis made prior to the experiment.

are shown in Table 1, which is scaled down for a total scanning time 20 seconds.

2.6. Experimental designs

Both the adaptive and constant speed control schemes were simulated without any operator's intervention. To carry out the manual control, two groups of operators were recruited: interventional radiologists and those without advanced medical training. Both groups went through the same training sessions and then performed five manual control experiments. The averages of the performance measures were used in the statistical tests.

2.7. Statistical test

The data collected by the Simulator was classified based upon the types of operators. The categories are interventional radiologists and those with little or no medical background. For the constant speed control scheme, we defined the following variables:

u_c = mean tracking error with the constant control scheme which is fixed for a given bolus data set. For each of manual control experiments, we define
u_{me} = mean tracking error with the manual control by experienced interventional radiologists,
u_{mn} = mean tracking error with the manual control by those with little medical training,
y_i = ith error of the manual control
S_{me} = sampled standard deviation of the manual control by interventional radiologists,
S_{mn} = sampled standard deviation of the manual control by those with little medical training, and
N = total number of manual control trials in each experiment.

Both the one sided and two sided statistical t-tests were performed. The purpose of the one sided test was to examine if the manual control could outperform the constant speed control. To this end, we assumed that the manual control error of each trial y_i, for either an experienced interventional radiologist or one with little medical training, was normally distributed. Then, it is well known that the variables

$$t_{me} = \frac{u_{me} - u_c}{S_{me} \big/ \sqrt{N}} \text{ and } t_{mn} = \frac{u_{mn} - u_c}{S_{mn} \big/ \sqrt{N}} \tag{1}$$

obey t-distributions [9,11]. Let the null hypothesis be that the manual control outperforms the constant speed control in terms of the mean error.

$$\begin{cases} H_{e0} : u_{me} = u_c \\ H_{e1} : u_{me} < u_c \end{cases} \text{and} \begin{cases} H_{n0} : u_{mn} = u_c \\ H_{n1} : u_{mn} < u_c \end{cases} \tag{2}$$

This is a typical t-test. Let α be defined as

$$\alpha = \text{Probability}(\text{reject } H_{e0} \text{ and accept } H_{e1}, H_{e0} \text{ is true})$$

and/or

$$\alpha = \text{Probability}(\text{reject } H_{n0} \text{ and accept } H_{n1}, H_{n0} \text{ is true})$$

and we can find $t_{1-\alpha,N-1}$ from the t-distribution from the statistical table. If $t_{me}(t_{mn}) < -t_{1-\alpha,N-1}$, we accept $H_{e1}(H_{n1})$ and reject H_{e0} (H_{n0}).

The two sided t-tests were also performed to examine if experienced interventional radiologist would do better than those with little medical training after several trial practices. The purpose of the test is to determine if an extensive training would be needed to operate manual controls effectively. To this end, let the null hypothesis be that two groups of operators perform similarly against that two groups of operators perform differently,

$$\begin{cases} H_{10} : u_{mn} = u_{me} \\ H_{11} : u_{mn} \neq u_{me} \end{cases}$$

In this case, we accept H_{11} and reject H_{10} if $|t_0| > t_{1-\alpha/2,N-1}$ where

$$t_0 = \frac{u_{mn} - u_{me}}{S_{mn} \big/ \sqrt{N}}. \tag{3}$$

3. Experimental results

With $N = 5$ or five trials, the mean error for constant control (u_c) is 186mm. The mean error for manual control by experienced interventional radiologists (u_{me}) is 66.4 mm. The mean error for manual control by those with little or no medical training (u_{mn}) is 72.4 mm. The standard deviation for manual control by experienced interventional radiologists (S_{me}) is 8.9. The standard deviation for manual control by those with little or no medical training (S_{mn}) is 8.7. Consequently, $t_{me} = -30$, $t_{mn} = -29.3$.

Let the probability to reject the null hypothesis even if the hypothesis is true be 0.05, or$\alpha = 0.95$. From the t distribution we found the corresponding $|t_0| = 1.54$, $t_{1-\alpha,N-1} = 2.132$, $t_{1-\alpha/2,N-1} = 2.776$. Clearly,

$$t_{me} = 7 - 30 < -2.132 = -t_{1-\alpha,N-1}, \quad t_{mn} = -29.3 < -2.132 = -t_{1-\alpha,N-1},$$
$$|t_0| = 1.54 < 2.776 = t_{1-\alpha/2,N-1}$$

which indicates there is no substantial difference between controls by interventional radiologists and by those with little or no medical experience. However, manual control does outperform the traditional constant speed control and is a strong candidate for future CTA.

4. Conclusion

By the above t-tests we have demonstrated that the manual controls, operated by either experienced interventional radiologists or those with little medical training, outperform the constant speed control. Furthermore, the manual control performance operated by experienced interventional radiologists is similar to that operated by those with little medical experience. In other words, no extensive training is required to operate our proposed manual controls. This statistical analysis suggests that our proposed technique can be readily implemented on clinical CT scanners for more flexibility and better performance in CT angiography.

In conclusion, we have developed a software CTA simulator that provides a realistic environment for testing various control schemes. In particular, it has been established that our proposed manual control mode is feasible, beneficial and operator-friendly for bolus-chasing CTA. Further work is underway to refine and transfer the technology into the diagnostic settings.

Acknowledgements

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References

[1] L. Kopka et al., Dual-phase helical CT of the liver: effects of bolus tracking and different volumes of contrast material, *Radiology* **201**(2) (1996), 321–326.
[2] P.M. Silverman et al., Assessment of a technology that permits individualized scan delays on helical hepatic CT: a technique to improve efficiency in use of contrast material, *AJR Am J Roentgenol* **167**(1) (1996), 79–84.
[3] E.W.J.B. Bai, R. McCabe, M. Sharafuddin, H. Bai, J. Halloran, M. Vannier, Y. Liu, C. Wang and G. Wang, Study of an adaptive bolus chasing CT angiography, *Journal of X-ray Science and Technology* **14**(1) (2006), 27–38.

[4] Z. Cai, M.R., G. Wang and E.W. Bai, *Bolus Chasing Computed Tomography Angiography Using Local Maximum Tracking Method*, 2007.
[5] J. Bennett et al., A Preliminary Study on Adaptive Field-of-View Tracking in Peripheral Digital Subtraction Angiograph, *Jounal of X-ray Science and Technology* **11**(1) (2003), 149–159.
[6] Z.J. Cai, G. Wang and B. EW, An adaptive optimal control design for bolus chasing computed tomography angiography, *IEEE Transactions on Control Systems Technology* (*To appear*) (2007).
[7] H.P. Dinkel et al., Optimizing liver contrast in helical liver CT: value of a real-time bolus-triggering technique, *Eur Radiol* **8**(9) (1998), 1608–1612.
[8] G.D. Schweiger, P.J. Chang and B.P. Brown, Optimizing contrast enhancement during helical CT of the liver: a comparison of two bolus tracking techniques, *AJR Am J Roentgenol* **171**(6) (1998), 1551–1558.
[9] M.P. Kimberlee Gauvreau, *Principles of Biostatistics*, 2nd ed. 2000: Thomson Learning College.
[10] Jen Dehaan and P.D. Haan, *Learning Actionscript 2.0 for Macromedia Flash 8*, 1st ed. 2005: Addison-Wesley. 848.
[11] D.C. Montgomery, *Design and Analysis of Experiments*, 6th ed. 2004: John Wiley & Sons Inc.