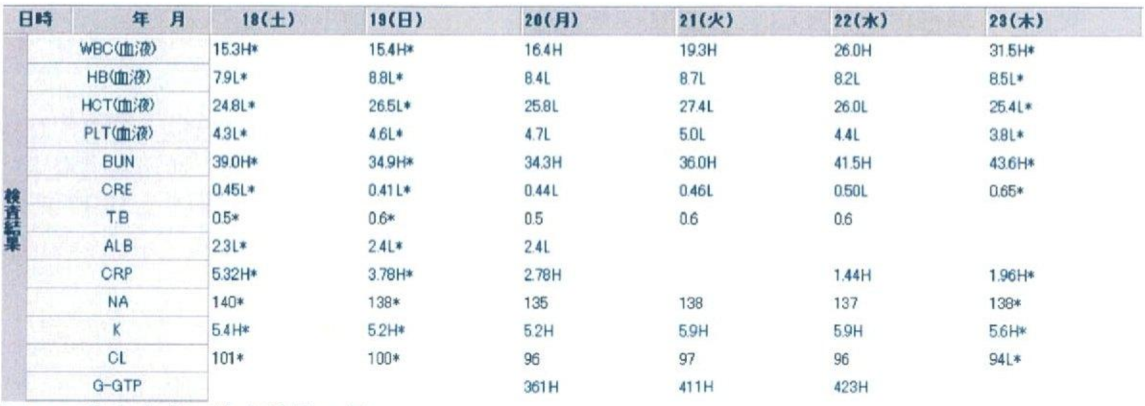
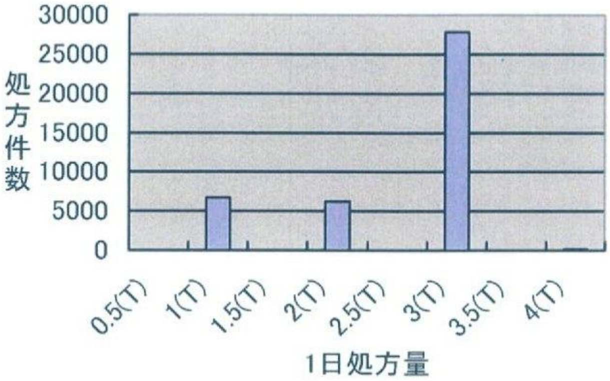


日時	年　月	18(土)	19(日)	20(月)	21(火)	22(水)	23(木)
検査結果	WBC(血液)	15.3H*	15.4H*	16.4H	19.3H	26.0H	31.5H*
	HB(血液)	7.9L*	8.8L*	8.4L	8.7L	8.2L	8.5L*
	HCT(血液)	24.8L*	26.5L*	25.8L	27.4L	26.0L	25.4L*
	PLT(血液)	4.3L*	4.6L*	4.7L	5.0L	4.4L	3.8L*
	BUN	39.0H*	34.9H*	34.3H	36.0H	41.5H	43.6H*
	CRE	0.45L*	0.41L*	0.44L	0.46L	0.50L	0.65*
	T.B	0.5*	0.6*	0.5	0.6	0.6	
	ALB	2.3L*	2.4L*	2.4L			
	CRP	5.32H*	3.78H*	2.78H		1.44H	1.96H*
	NA	140*	138*	135	138	137	138*
	K	5.4H*	5.2H*	5.2H	5.9H	5.9H	5.6H*
	CL	101*	100*	96	97	96	94L*
	G-GTP			361H	411H	423H	

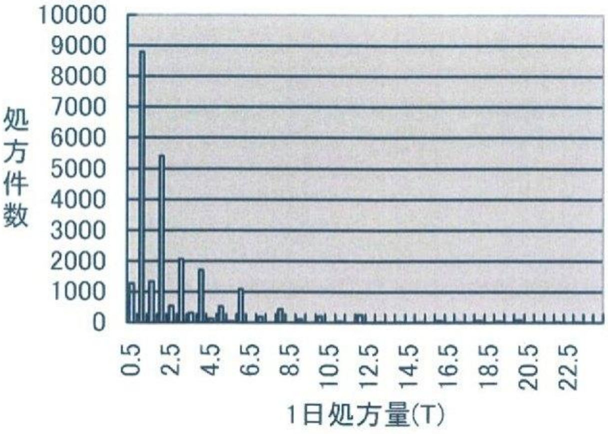
図17　重症患者の検査結果の例

標準に範囲から逸脱している値の背景をグレーで示している。標準範囲からの逸脱を基準に警告すると、ほとんどすべての検査について毎日警告が行われる。



基本統計量	
平均	2.52
中央値	3
標準偏差	0.763662
最小	1
最大	4

図18　薬剤Aの分布と統計量



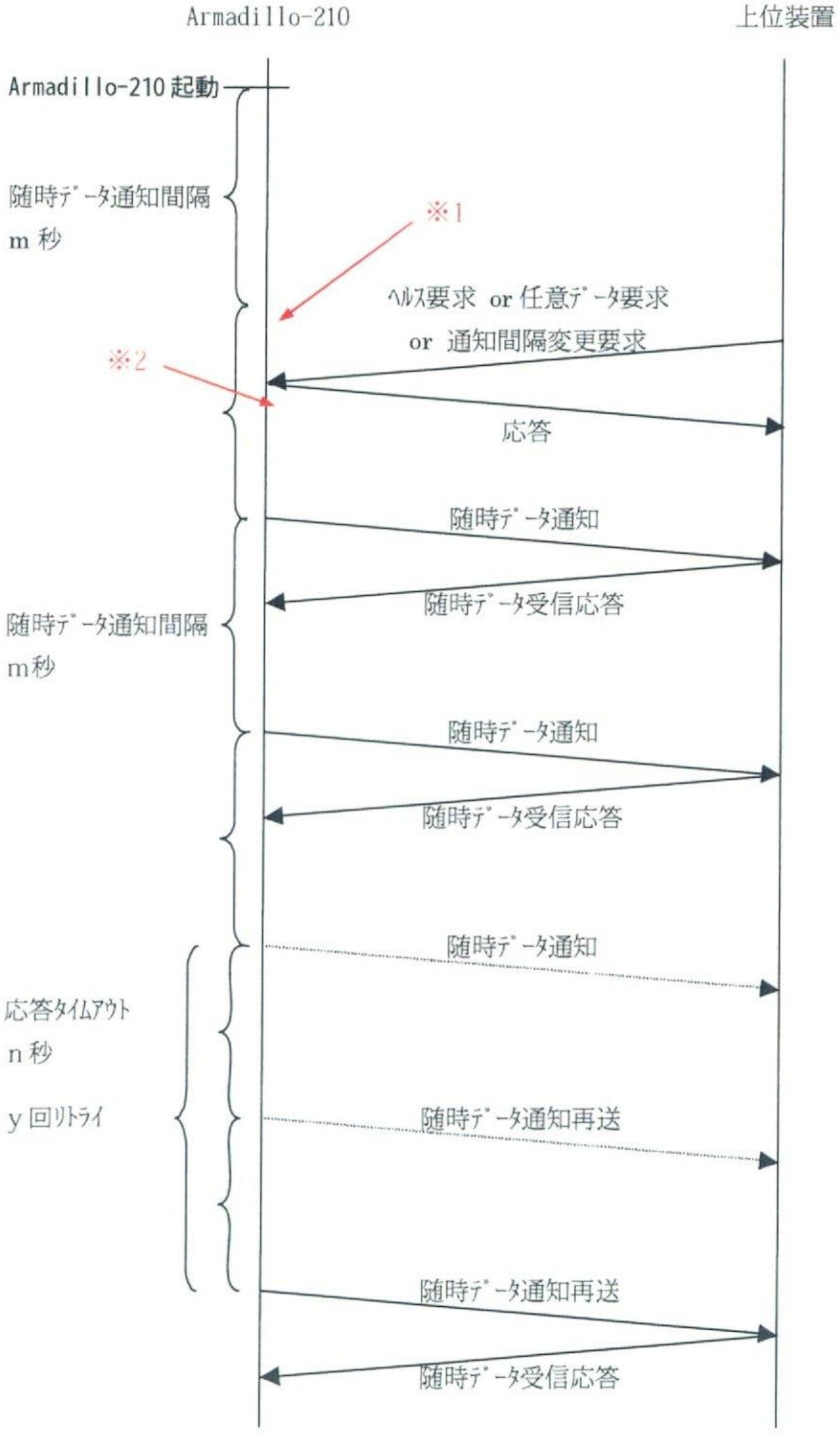
基本統計量	
平均	2.65
中央値	2
標準偏差	2.861032
最小	0.5
最大	24

図19　薬剤Bの分布と統計量

資料1.　輸液ポンプとの通信仕様とシステム構成

1）　輸液ポンプとの随時データ通知フロー

Armadillo-210から上位装置に対し、現在の「輸液ポンプ基本動作状態」を指定間隔毎に送信する。随時データ通知間隔の規定値は1800秒（30分）とし、通知間隔変更要求コマンドにより変更を可能とする。但し、随時データ通知は上位装置からArmadillo-210に対し、何れかのコマンド送信後から行われるものとする。

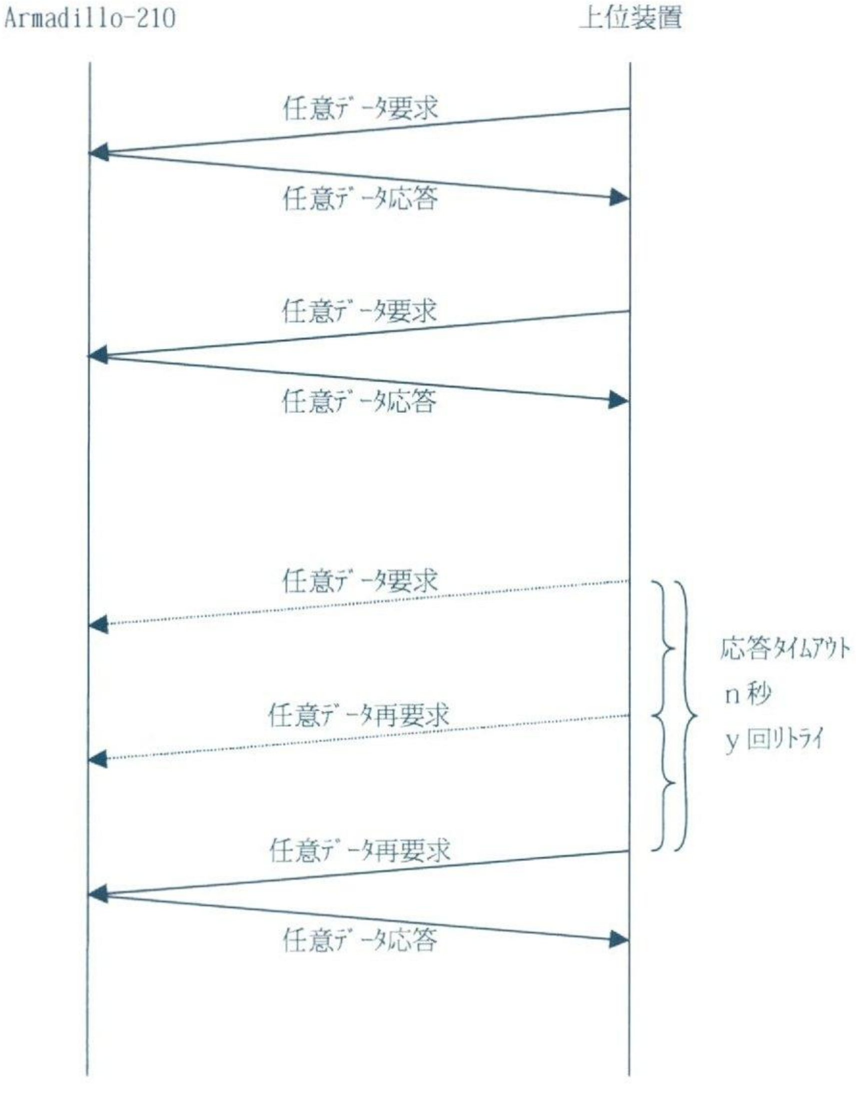


※1　このﾀｲﾐﾝｸﾞではは随時ﾃﾞｰﾀ通知を行わない

※2　上位装置からの何れかのｺﾏﾝﾄﾞ受信後、随時ﾃﾞｰﾀ通知が開始

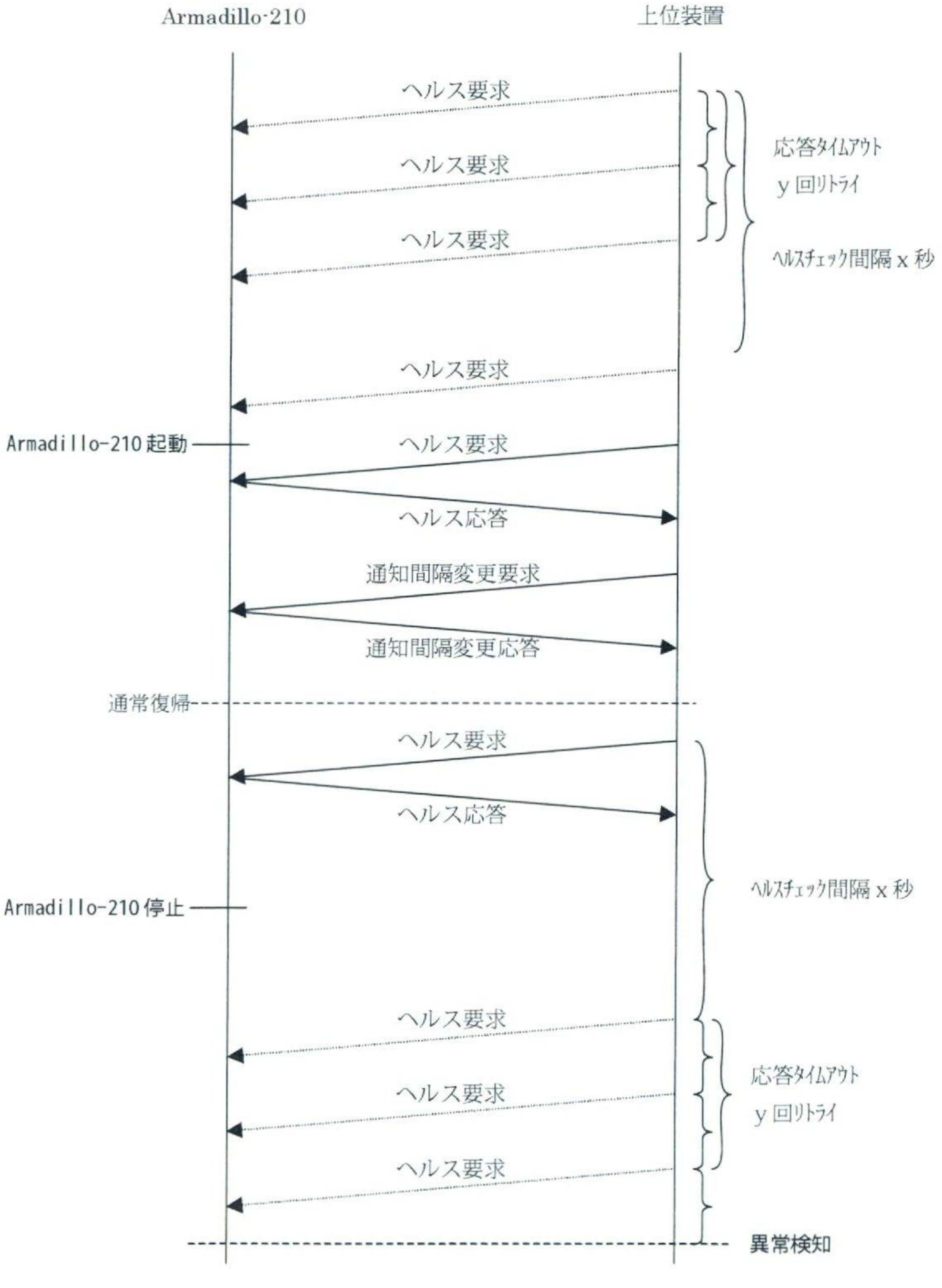
2）　輸液ポンプへの任意データ要求

上位装置からArmadillo-210に対し、現在の「輸液ポンプ基本動作状態」データを要求する。この要求により上位装置は任意のタイミングで「輸液ポンプ基本動作状態」データを取得する。

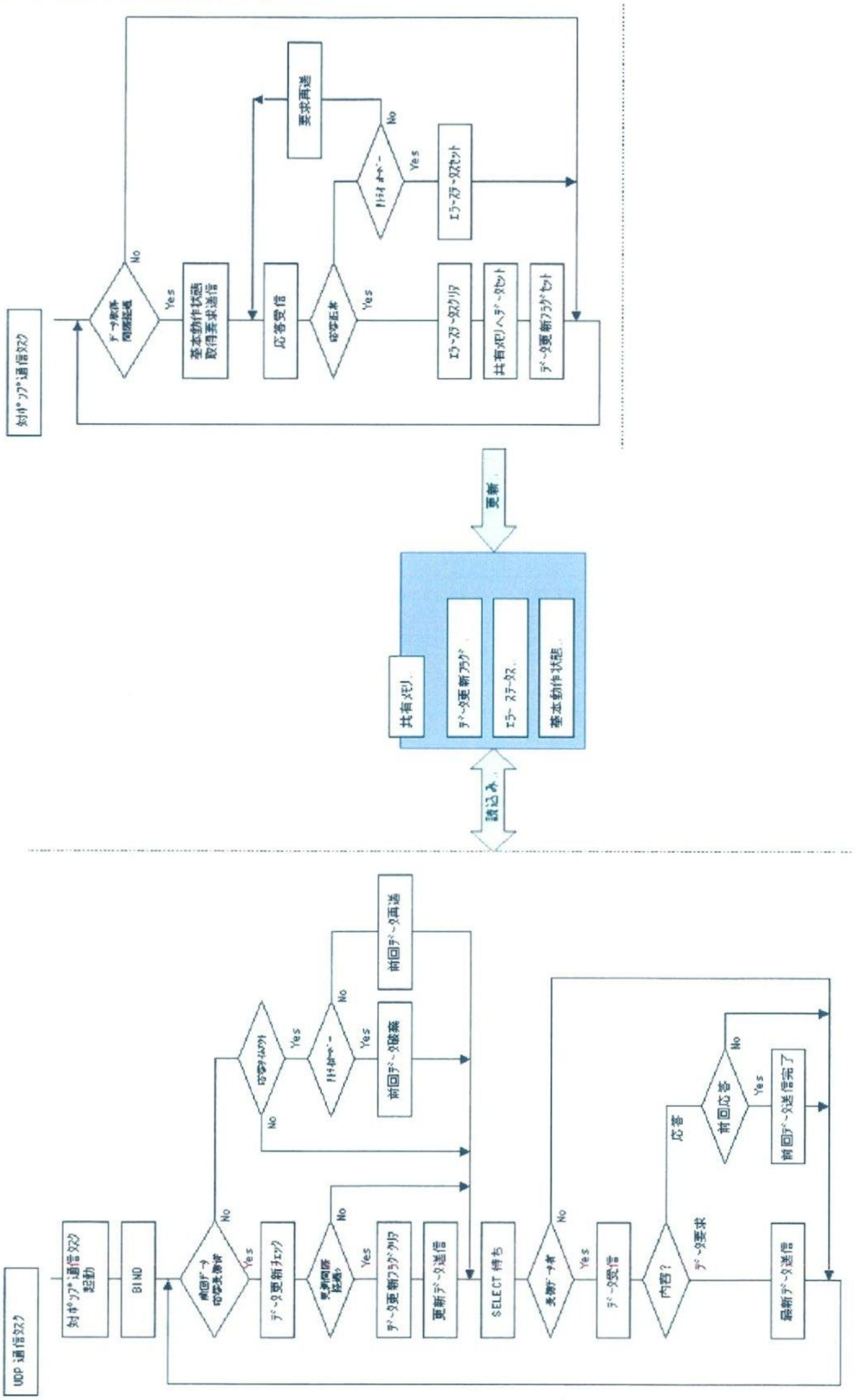


3）　輸液ポンプの生存状態問い合わせ（ヘルス要求）

上位装置から Armadillo-210 に対し、ヘルスチェック要求を送信することにより、Armadillo-210 の生存確認を行うことを可能とする。



4）．システム全体の概略フロー



別紙4

研究成果の刊行に関する一覧表

雑誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Hori K, Kuroda T, Oyama H, Ozaki Y, Nakamura T, Takahashi T	Improving precise positioning of surgical robotic instruments by a three-side-view presentation system on telesurgery.	J Med Syst	29(6)	661-670	2005
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田中勝弥、耿景海、松谷司郎、大江和彦	医療安全を目的とした輸液ポンプ動作監視システムの開発.	医療情報学	26(Spl)	925-926	2006

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Improving Precise Positioning of Surgical Robotic Instruments by a Three-Side-View Presentation System on Telesurgery

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For faultless collaboration among the surgeon, surgical staffs, and surgical robots in telesurgery, communication must include environmental information of the remote operating room, such as behavior of robots and staffs, vital information of a patient, named supporting information, in addition to view of surgical field. "Surgical Cockpit System," which is a telesurgery support system that has been developed by the authors, is mainly focused on supporting information exchange between remote sites. Live video presentation is important technology for Surgical Cockpit System. Visualization method to give precise location/posture of surgical instruments is indispensable for accurate control and faultless operation. In this paper, the authors propose three-side-view presentation method for precise location/posture control of surgical instruments in telesurgery. The experimental results show that the proposed method improved accurate positioning of a telemanipulator.

KEY WORDS: telesurgery; robotic surgery; Surgical Cockpit System; three-side-view; precise instruments positioning.

INTRODUCTION

In telesurgery, a teleoperating surgeon to operate a surgical robot placed in a room, called "operator site," is spatially separated from a patient and other surgical staffs in a remote operating room, called "operation site," and information network connecting the two sites enable the surgeon to operate the patient. The surgeon

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needs to understand motion of surgical instruments, conditions of the patient, and other status in the operation site. For faultless collaboration among the surgeon, surgical staffs, and surgical robots in telesurgery, communication must include environmental information of the operating site, such as behavior of robots and staffs, vital information of a patient, named supporting information, in addition to view of surgical field.

The authors have been developing a telesurgery support system named "Surgical Cockpit System"(Fig. 1).(1) The Surgical Cockpit System consists of three fundamental subsystems, operating-field subsystem, robot subsystem, and surgical-environment subsystem. The operating-field subsystem provides view around operating-field and target organs. The robot subsystem supports manipulation of surgical robots, teleinstruction tools, and other tools for telesurgery. The surgical-environment subsystem, the peculiarity of the Surgical Cockpit System, provides multipurpose information display, which visualizes any kinds of additional information such as panoramic view of the operating room, multiangle presentation of the target of the patient, virtual surgeon guides, vital information of the patient, and so on. In this report, methodology of live video presentation is discussed for information supporting on the surgical-environment subsystem.

To obtain precise location/posture of surgical instruments relative to target is indispensable for accurate control and faultless operation. Therefore, visualization method to give precise location/posture plays important role in telesurgery support system. Foregoing research of the authors proposed to integrate two types of view, that is, detailed view of the target and wide-angle view around the target.(1) Experimental results show effectiveness of the proposed method for roughly positioning of the end effector and detailed approach. However, location/posture control of surgical instruments is quite difficult on the former method. It is because to recognize current location/posture of surgical instruments is quite difficult under single view environment provided by former prototype (Fig. 2).

The purpose of this paper is to propose multiview system for precise location/posture control of surgical instruments in telesurgery, and evaluate the effect of proposed method.

METHODS

This study proposes to use three-side-view presentation in addition to circumstantial view for supporting location/posture recognition, and evaluate effectiveness of three-side-view presentation on telerobotic operation.

To present the depth of the target to a teleoperating surgeon, multiangle presentation is required. A three-side-view method is a multiangle presentation method mainly used for solid shape design. Three-side-view consists of front view, side view, and top view. Three-side-view presentation for telerobotic surgery eases recognition of relative posture between target organ and surgical instruments.

In this research, three-side-view was applied for presenting relative posture around operating-field. Live video images of the operating field and the operating table were integrated into a multiplexed image with four segments; three segments

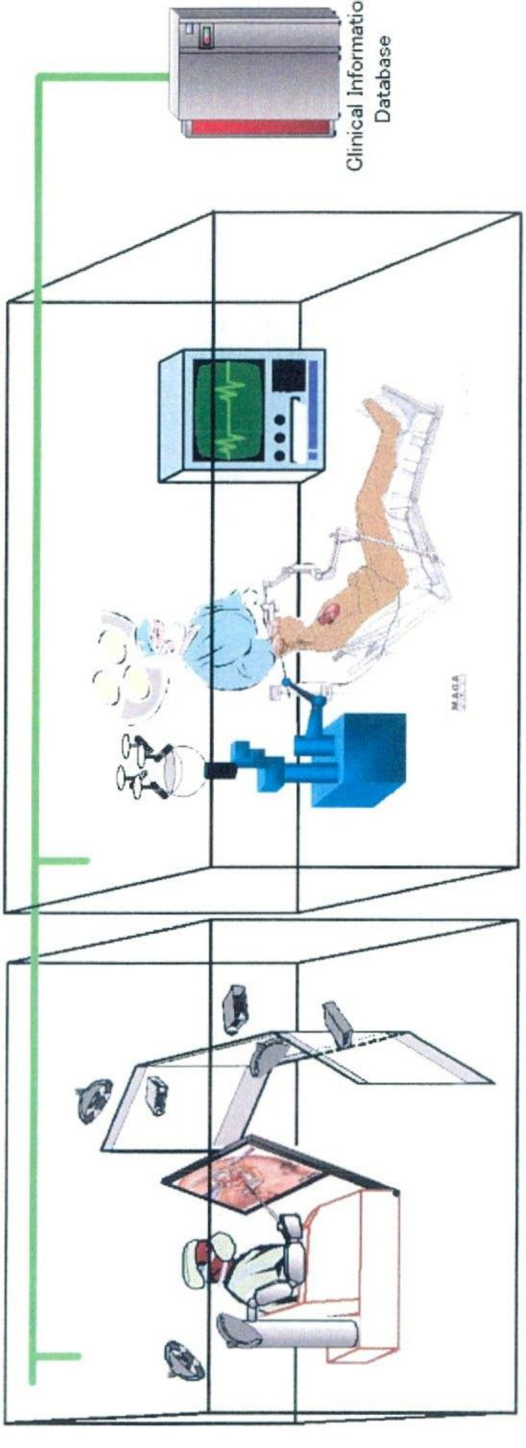


Fig. 1. Concept of Surgical Cockpit System.

Fig. 2. Single view environments in Surgical Cockpit System.

were used to display three-side-view and the other segment was used to display around an operating table (Fig. 3). For evaluating three-side-view presentation, the proposed method was compared with wide-view immersive presentation around an operating table, which is proposed in the foregoing research. The conditions of presentation method in the experiment were named wide-immersive mode and three-side-view mode. In wide-immersive mode, enlarged live video by a wide-angle camera was displayed on multidisplay system with three screens placed side by side (Fig. 2). The size of each screen is 60 inches. The resolution is SXGA (1280 × 1024). Live video was captured and mapped on a virtual rectangular screen by OpenGL function to display enlarged video. The format of video signal is NTSC. In three-side-view mode, multiplexed image was displayed on a center screen of three side-by-side screens used in wide-immersive mode. Detailed view of operating field was provided by operating-field subsystem.

The evaluation was performed under delayed-video conditions. Subjects were 5th grade students of medical school of Kyoto University. The conditions of video streaming delay were no-delay condition and satellite condition. In no-delay condition, live video was presented without delay. In satellite condition, delay consisted of MPEG-2 encoding/decoding delay and satellite communication delay. The measurement of MPEG-2 encoding and decoding time shows that the delay of MPEG-2 encoding and decoding is about 500 ms. Round trip time from Kyoto University,

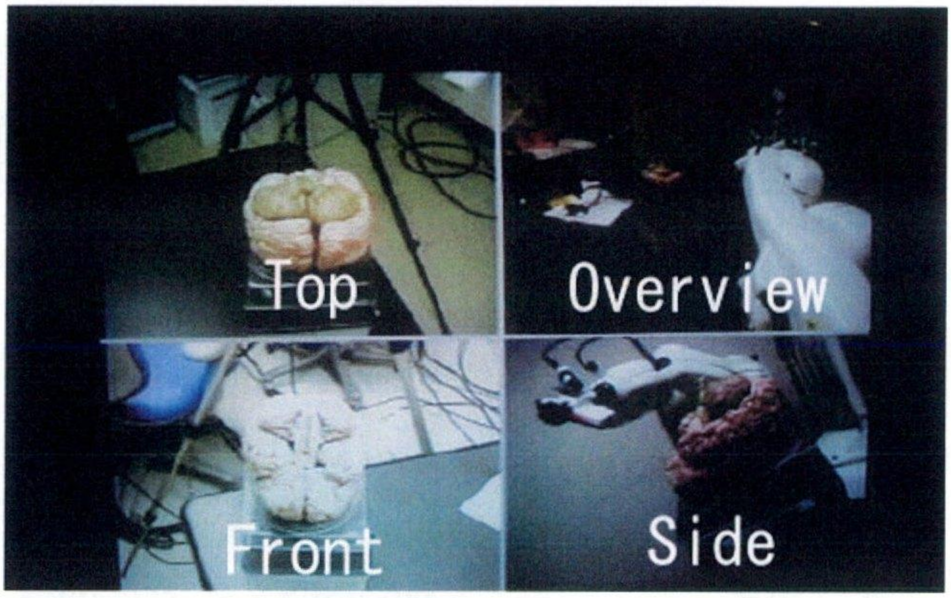


Fig. 3. Three-sides-view of operating field.

Kyoto, Japan, to Institut of Teknologi Bandung, Bandung, Indonesia, which is connected over satellite communication served by AI3 project$^{(2)}$ shows that approximate transmission delay over satellite communication is 250 ms. Therefore, the satellite-communication delay was decided to be 250 ms. Total delay on satellite condition was 750 ms. The delay was artificially appended by a delay generator between MPEG-2 encoder and decoder (Fig. 4).

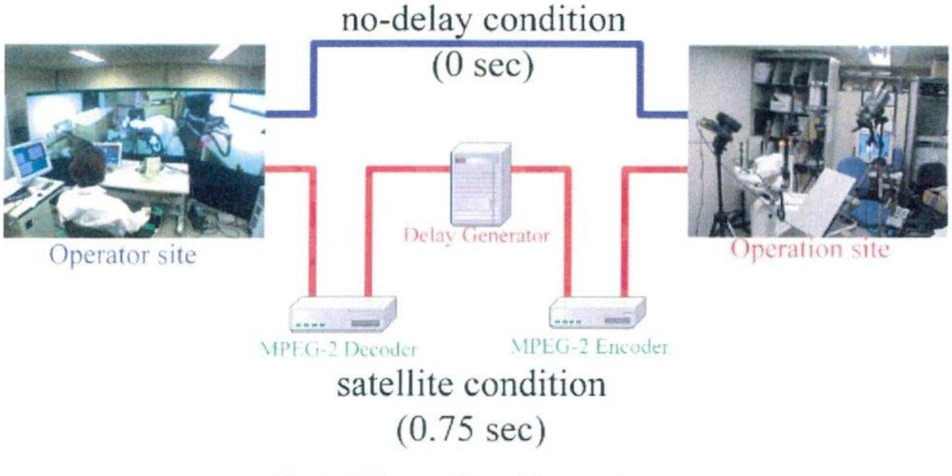


Fig. 4. Delay condition of the experiment.

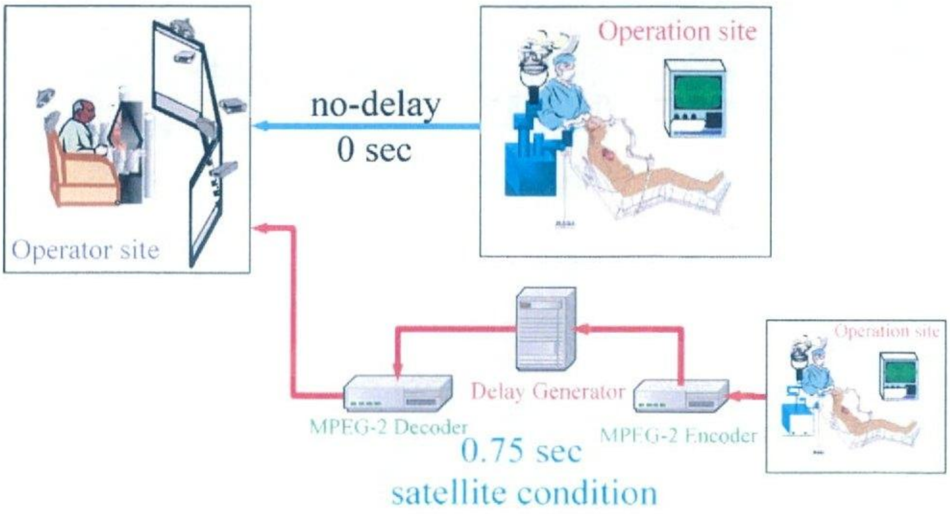


Fig. 4. Continued.

The experimented conditions were four combined conditions of presentation modes and network delay conditions, wide-immersive mode with no-delay condition (WN), wide-immersive mode with satellite condition (WS), three-side-view mode with no-delay condition (TN), and three-side-view mode with satellite condition (TS).

A task scenario of the experiment was a target-pointing task that assumes centesis. Each subject tried to apply tip of an instrument to a target area. The target area was 1.5 cm in diameter (Fig. 5). Each subject was instructed to adjust an instrument perpendicularly on the target area.

Four conditions were evaluated by comparing posture of an instrument at the end of the task (final posture), time to finish the task (task achievement time) among the four conditions, and by sensory evaluation of the subjects.

The final posture was evaluated by error angle between the normal line on the target area and the direction of the instrument in the final posture. The task achievement time was defined as time whole process time of the task. Final posture and task achievement time were analyzed with nonparametric test by SPSS. Rejection ratio was 0.05.

In the sensory evaluation, incongruous sense of given view, drivability of the robot, and easiness of spatial recognition were evaluated by cyclic paired comparison. The cyclic paired comparison is a paired comparison method with minimum sets of compared pairs.(3) For the cyclic paired comparison, evaluated conditions should be compared in cyclic order. In the experiment, the order of conditions was {WN, WS, TS, TN, WN}. The last WN condition could be used to evaluate learning effect for evaluation of final posture and task achievement time.

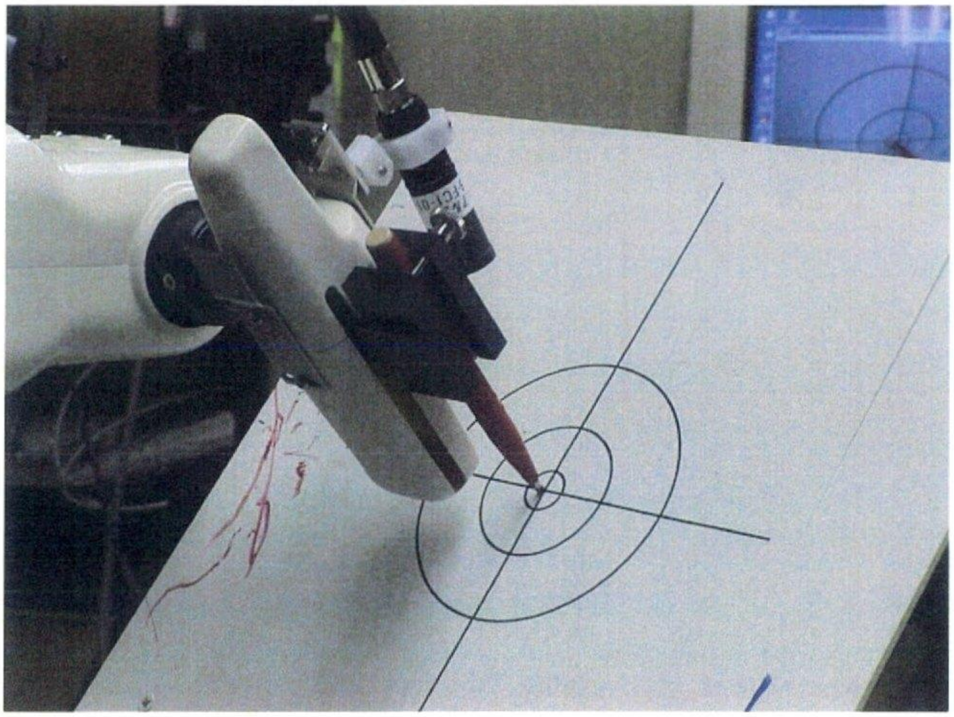


Fig. 5. Target positioning task in the experiment.

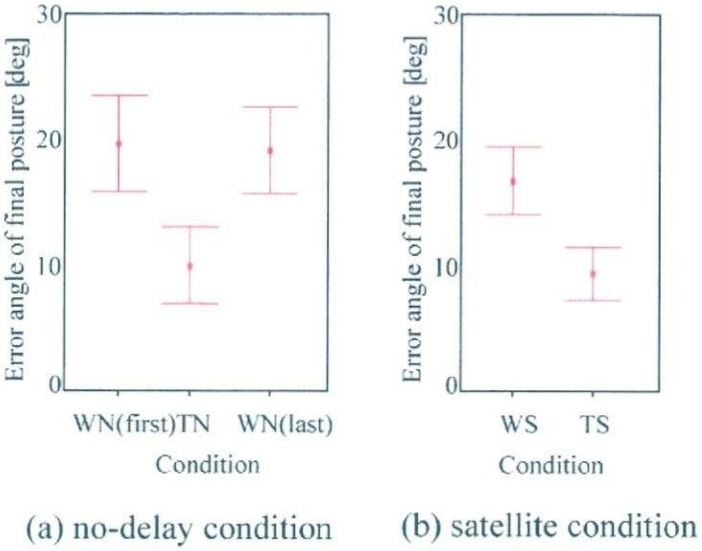
RESULTS

For final posture, conditions of presentation methods were statistically different in error angle of the final posture (Fig. 6(a), (b)). The error angles under three-side-view modes were significantly smaller than results under wide-immersive modes for each of no-delay condition and satellite condition. As per the results, the three-side-view presentation was good at the accurate control of the instrument posture.

For task achievement time, each set of conditions {WS, TS} and {WN (first), TN} had no statistical difference (Fig. 7(a), (b)). The task achievement time under TN conditions was significantly longer than the last WN condition (Fig. 7(a)). The first WN condition and the last WN condition were statistically different in task achievement time. The results show that learning effects affected task achievement time through the experiment. On the other hand, conditions of presentation methods did not affect for task achievement time.

By sensory evaluation, orders in each set of {WN, TN} and {WS, TS} were observed for incongruous sense of given view, drivability of the robot, and easiness of spatial recognition (Fig. 8).

For incongruous sense of given view (Fig. 8(a)), significant differences were not confirmed in both sets of {WN, TN} and {WS, TS}. However, WN conditions were a little more incongruous than TN conditions, and WS conditions were a little more

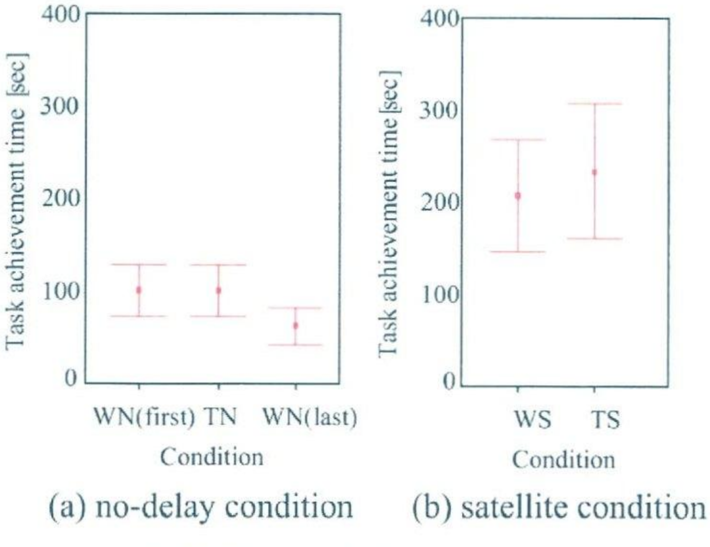


(a) no-delay condition (b) satellite condition

Fig. 6. The results of error angle of final posture.

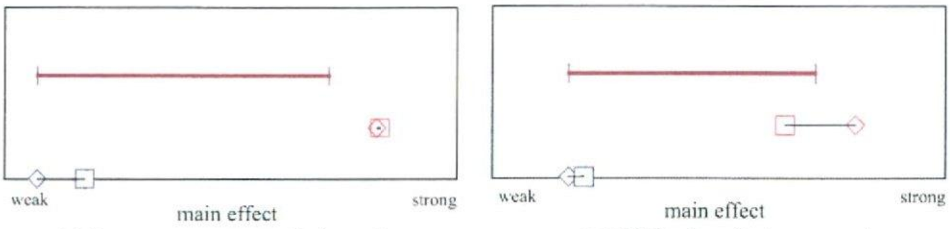
incongruous than TS conditions. In conclusion, the three-side-view presentation was not significant but a little more effective than the wide-immersive presentation.

For drivability of the robot (Fig. 8(b)), each set of {WN, TN} and {WS, TS} was at similar order on the observed order. The results showed that three-side-view presentation was not effective for drivability of the robot. Significant differences were not confirmed. Impressions of the subjects show that much relative location/posture

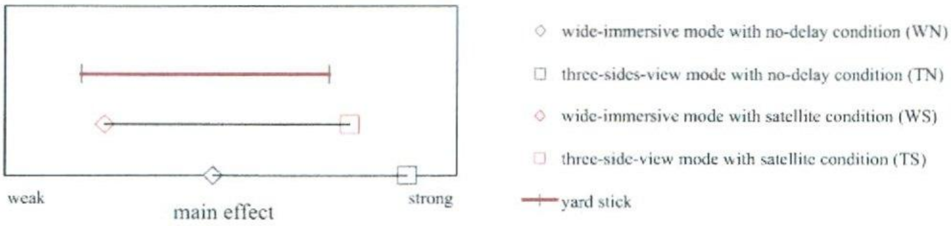


(a) no-delay condition (b) satellite condition

Fig. 7. The results of task achievement time.



(a) Incongruous sense of given view (b) Difficulty of robot control



(c) Easiness of spatial recognition

Fig. 8. The result for sensory evaluation.

information was provided in the three-side-view presentation; however surplus information increased the complexity of the given view. In the three-side-view presentation, the display area was divided into four sections. The display layout was complex and the display size for one camera view was reduced.

For easiness of spatial recognition (Fig. 8(c)), TN conditions tended to be a little easier than WN conditions, and TS conditions tended to be a little easier than WS conditions. In both sets significant differences were not confirmed. The results show that the three-side-view presentation was not significant but a little easier for spatial recognition than the wide-immersive presentation.

The results and the impressions showed that the spatial recognition could be difficult by the view complexity caused by the three-side-view under stressful condition such as video-delayed condition. The difficulty of the spatial recognition caused the declination of robot drivability and inclination of incongruousness in given view. The three-side-view presentation method would be able to support relative location/posture recognition, but the complexity of three-side-view could cause difficulty of spatial recognition and robot control.

CONCLUSION

In this research, the three-side-view presentation method was proposed. The three-side-view can present relative location/posture precisely.

The effect of the three-side-view was evaluated. As the results of the experiment, the three-side-view presentation did not affect for operation time under a teleoperation task with delayed video presentation. For accurate pointing task, the three-side-view presentation improved the accuracy of the final posture of surgical instruments. As sensory impression of a surgeon, the three-side-view would be a little helpful but a little complex in spatial recognition. The three-side-view presentation was effective for accurate pointing task.

The complexity of the spatial recognition could cause difficulty of robot control. For effective support of spatial recognition in telesurgery, the evaluations of other presentation methods are required. In future research, effective presentation methods and video switching strategies in optimum timing should be studied for supporting spatial recognition of a teleoperating surgeon under video-delayed environment.

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Interaction model between elastic objects for haptic feedback considering collisions of soft tissue

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KEYWORDS
Virtual reality;
Medical simulation;
Haptic display;
Elastic body;
Interaction

Summary The simulation of organ—organ interaction is indispensable for practical and advanced medical VR simulator such as open surgery and indirect palpation. This paper describes a method to represent real-time interaction between elastic objects for accurate force feedback in medical VR simulation. The proposed model defines boundary deformation of colliding elements based on temporary surface forces calculated by temporary deformation. The model produces accurate deformation and force feedback considering collisions of objects as well as prevents unrealistic overlap of objects. A prototype simulator of rectal palpation is constructed on general desktop PC with a haptic device, PHANToM. The system allows users to feel different stiffness of a rear elastic object located behind another elastic object. The results of experiments confirmed the method expresses organ—organ interaction in real-time and produces realistic and perceivable force feedback.

1. Introduction

Virtual reality (VR) technologies enable physicians to interact with flexibly customized simulated environments based on visual, auditory and haptic feedback without potentially harmful contact with real patients. For this reason, VR-based simulation has

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doi:10.1016/j.cmpb.2005.09.001

attracted considerable attention as a key technology for the advancement of medical treatments and improvement of quality of human life. In the field of medicine, VR simulators are applied for uses such as education, therapy and rehabilitation, procedural training, surgical planning, rehearsal, and interoperative support [1,2]. Though many simulators have been developed, and a few even commercialized [3–6], most have dealt with single organ objects without handling collisions between multiple organ objects [4–9]. This makes them unsuitable for VR simulation of the human body, a system with many organs which often collide. Haptic feedback is especially important in delicate surgical pressures requiring fine sensations, especially when slightly excessive pressure can injure a patient. Haptic sensation is also significant in palpation: as the physician examines the characteristics of an organ beneath the body surface with the tips of his or her fingers, collisions of the soft tissues are inevitable. This paper proposes a model of interaction between soft tissues, in order to provide a virtual environment simulating haptic feedback from the collisions of soft tissues.

Palpation and surgery simulations require the use of physics-based deformable models to accurately calculate the deformation and force caused by physical action on soft tissue. This adds considerably to the challenge of simulation, however, as physics-based deformation models generally require more computations than the geometry-based deformation models used in computer graphics. A comprehensive simulation of multiple characteristics of soft tissue all at once is tremendously difficult. Elasticity, a property related to force and displacement, is one of the most important characteristics of soft tissue. Accordingly, this paper treats soft tissues as elastic objects and seeks to model the interactions between them. The interaction model presented here must perform three important functions.

1. To allow interactive manipulation in real-time.
2. To take into account the physical properties of colliding objects.
3. To produce an adequate visual reality.

Interactive manipulation, an operation performed in both palpation and surgery, requires real-time computation of soft tissue deformation and reaction forces. When a soft elastic object and a hard object collide, the former deforms more, as shown in Fig. 1. In addition, the reaction forces during the collision depend on the extent of the deformations in the collision area. Thus, the interaction model must represent the deformation on the basis of the physical properties of both elastic objects. Visual reality is one of the most important functions for effective simulation. Excessive invasion of colliding objects must be avoided.

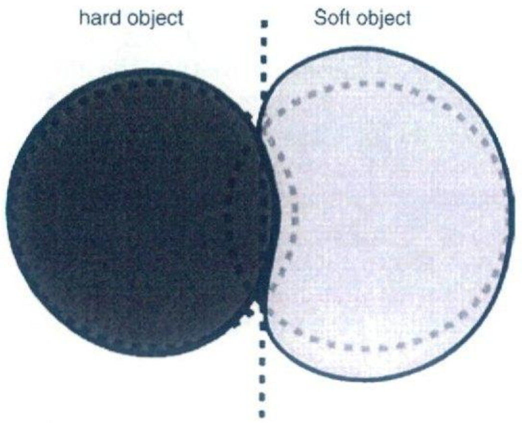


Fig. 1 Deformation caused by collision of elastic objects with different stiffnesses. The soft object deforms more than the hard object.

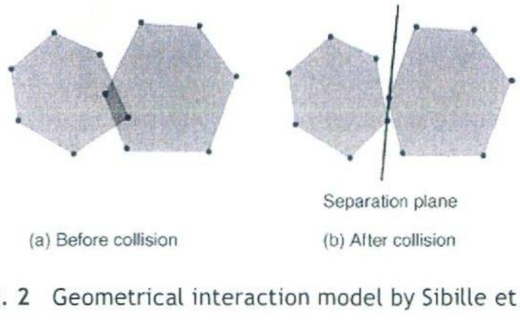
In this paper, we propose an interaction model between elastic objects that performs the above functions. After describing the proposed model, we evaluate its performance and validity by applying it to the development of a rectal palpation simulator.

2. Background

The simulation of physical phenomena has been a key technology to enhance visual and haptic reality in medical simulations. Studies in biomechanics and computer graphics in the field have devoted particularly close attention to soft tissue modelling [10–13]. Many kinds of physics-based deformable models have been proposed for deformation and force feedback [13–19]. One such model, the mass-spring model, represents an object as points of mass joined by springs [15,16]. Though effectively applied for a variety of uses, the model does not perform adequately when simulations require accurate calculation of deformation and reaction force [7]. The mass-spring model also requires fine-tuning of physical parameters to represent certain physical characteristic, and improper parameter values lead to system instability. The boundary element model (BEM) and long element model (LEM) have also been proposed for deformation and force feedback. Though both are capable of fast computation [12,17,18], they have limitations in surgical and palpation simulations. An organ with internal lesions possesses several distinct physical properties, yet BEM assumes that an organ is homogeneous. Organs also tend to be complex in shape, yet LEM is poor at representing anything but simple shapes. A fourth alternative, the finite element (FE) model, has been regarded as the most accurate model for many years, but it is also the most computationally expensive [19]. Thankfully, recent progress of computers and computational methods has improved the outlook. With innovations such as condensation and Hirota's method [19,20], computation and simulation with haptic interaction can now be performed in real-time by the FE method.

Thousands of studies in mechanical engineering and VR have focused on the interaction between elastic objects. None, however, have been able to theoretically solve the contact problem. While the Hertz theory [21] is sometimes applied to the contact problem for convenience, it cannot be applied for arbitrary shapes. In VR simulation, several methods for describing collision responses have been proposed for the modelling of interactions between elastic objects [22,23]. Sibille et al. solve the contact problem by projecting colliding nodes to a plane which passes the barycenter of the colliding nodes and is oriented perpendicularly to the average normal vector of the colliding nodes (see Fig. 2) [22]. Though effective in curtailing the invasion of colliding objects, this method models deformation and haptic force based on geometrical information rather than information on the actual physical properties of the objects. Joukhadar et al. apply forces proportional to the invading volume of colliding objects onto the surfaces of the objects [23]. Their method fails to consider the physical properties of the volume, however, and it does not permit real-time computation of the invading volume (as they describe in their paper). Overall, the existing methods do not seem to provide adequate solutions for the above functions.

None of the rectal palpation simulators so far developed [24,25] have attempted to simulate the deformation and interaction between the rectum and prostate. This functional limitation compromises the flexibility of the simulation conditions and obfuscates the visual and haptic realities.



(a) Before collision (b) After collision

Fig. 2 Geometrical interaction model by Sibille et al.

3. Design considerations

There are two ways to represent multiple organs: with a single elastic object representing multiple organs or with multiple elastic objects representing multiple organs.

Several simulators [26,27] use the former method, treating multiple organs as a single elastic object. Methods which rely on the filling of finite elements into gaps between elastic objects are unsuitable in situations where contact regions often change. When the contact regions of organs are changed, the topology of each object changes and the global stiffness matrix needs to be reassembled. It also becomes necessary to re-compute the pre-processing stage, including the inversion of the global stiffness matrix [20]. This presents a significant problem, as the re-computation is generally slower than the haptic refresh rate (about 300 Hz) [2]. As an added problem, limitations in storage volumes would make it extremely difficult to pre-compute and store all of the possible models. Given the representation capabilities and resources of today's computers, we conclude that multiple organs must be modelled as multiple independent objects.

4. Computational methods

4.1. Interaction model between elastic objects

Our interaction model between elastic objects focuses on physics-based force feedback taking into account the physical properties of colliding objects. We define "interaction" as the process which determines the deformation in the collision area based on the physical properties of the colliding objects. Though the extent of deformation by collisions is theoretically unsolved, as mentioned earlier, it presumably depends on the physical properties of the colliding objects. Thus, the deformation is determined based on surface forces temporarily calculated by specifying temporary displacements, where surface forces are derived from physical properties and can be calculated rapidly by the finite element method using Hirota's model [20]. Collisions are detected by testing whether a node has moved into the internal side of the surface of another object.

The illustration in Fig. 3 outlines the proposed model. The actual displacements of the colliding elements of object A, B are calculated as $|\vec{b}| : |\vec{a}|$. The displacements are thus given to the elements