Service Robotics and Mechatronics
Keiichi Shirase · Seiji Aoyagi

Service Robotics and Mechatronics

Selected Papers of the International Conference on Machine Automation ICMA2008

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Preface

It is our great pleasure to hold the 2008 International Conference on Machine Automation at Awaji Yumebutai International Conference Center. The conference is held every 2 years in Finland and Japan by turns, and this is the 7th conference sponsored by Kansai University and the Japanese Council of International Federation for Theory of Machines and Mechanism, in cooperation with 6 academic societies and 2 institutes and organizations.

In a society with declining birth rate and rapidly aging population, even the senior citizen need to take up active roles in daily life and social activities. In order to provide a safe living environment for them, and for those who are handicapped, new technologies that can support their activities adequately are required. Furthermore, in order to facilitate coexistence between man and machine, the design and application of systems that take into account human psychology and movement need to be considered. The shape and movement of the support robots that assist human beings in daily life must be designed with judgment on the effects of their applications on human psychology. While more detailed surveillance are required for monitoring system that monitor the daily life of human beings and the safety of the society, it is also important that such systems do no overburden those being monitored. In addition to those, mechatronics is also highly applicable in the area of reconstruction works after disasters, and restoration works on polluted or abandoned environment due to chemical substances, land mines or other factors. In production plant, it is expected the workers’ burden can be reduced by implementing autonomous distributed or unmanned factory. Simply put, in order to ensure peace and safety to human society, the next generation robotics and mechatronics systems are required to systematically analyze human psychology and movement, and based on these results new system and machines will be developed.

This conference focuses on the topics and applications of such service robotics and mechatronics, and 79 papers are accepted after careful screening for the presentation in 18 technical sessions including rehabilitation, medical applications, robot, manufacturing, sensor, control, simulation, etc. Finally, two keynote papers and 66 papers are selected to publish the book titled “Service Robotics and Mechatronics” after the conference.

We would express our sincere appreciation and thanks to all the members of the Advisory Committee, the Organizing Committee, the Program Committee, the reviewers, the chairs, and the staffs as well as the participants for their good contribution and supports to hold this exciting conference.

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Designing Mobile Work Machines in Cyber Space

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Abstract
Rapid development in ICT has made possible to accomplish detailed simulations of complete machine system in meaningful time and effort. Due to this, mechanical structures, power transmission, actuation and control systems can be designed more precisely. Furthermore, real-time simulation and hardware-in-the-loop simulation has enabled including of a human operator and real control system on the simulation. VR-technology together with user-centred design methods enables constructing of machines with good user experience.

Keywords:
Virtual Design; Mobile Work Machine, User Experience, Virtual Reality

1 INTRODUCTION
In most products of Mechanical Engineering the Time-to-Market and an understanding customer needs are today major factors in product success [1]. The speed of design process is very much gained during past 10 years due to development in 3D CAD, modelling and simulation methods. Functionality of rather complex machine can be simulated off-line which improves to optimize the design and reduce uncertainty. Increasing of computation power has made it possible to real-time simulation of simpliﬁed machine systems. This has enables hardware-in-the-loop simulations where part of the real machine can be simulated against simulation models, Figure 1.

Figure 1. Phases in simulation based product development.

Cyberspace is virtual dimension created by computers and their interconnections such as Internet. In engineering this can be used for evaluation of prototypes by mathematical product models and Visualization. This will become more useful due to technical development:
• In 10 years time computational cost will be reduced with a factor of 1000.
• Internet backbone speed will be increased with a factor of 100.
The design will also be done distributed globally in collaborative context.

2 MOBILE MACHINES IN FINLAND
Typical mobile machines made in Finland, as shown in Figure 2, are highly specialized and they produced in small series. Often concurrent engineering is needed because there are number of different engineering teams attending design of such machines. Designing the control cabin of a mobile machine itself is challenging because it necessitates numerous trade-offs that need to be done between the various design quantities such as visibility, functionality, ergonomics, safety and industrial design.

Figure 2. Mobile Machine.
Mobile Machines are challenging objects for Virtual Design due to their small series and rather tight time schedule which then leaves not much time and effort for Virtual Design. Therefore the machine design process need to be rethink so that there are more resources and time reserved at begin of the project for finding the customer needs and checking the plan. This time will be saved when revisions and corrections need not do be done at the end of the process.

At the moment Mobile machines are mainly manually driven machines. However, there is already number of teleoperated semi-autonomous machines which do not need a human driver but which need remote control by a human operator. Examples of this can be found from mining and harbour equipments. Next step of the development are fully autonomous machines which do not need human supervision. Due to complexity of their work environment there are no examples of this in Mobile Work Machines but in housekeeping there are already a hovering machine and lawn mower. As a next step in development is a autonomous machine group which is capable to operate together without human control, Figure 3. Complexity of even manually driven machines will increase as a function of time because more work supporting functions based on ICT will be added. As a result, complexity of Mobile Work Machines will increase significantly.

3 TESTING OF CONTROL SYSTEM

Complexity of control system makes their testing very challenging. First, in distributed control system also the software is distributed in number of Electronic Control Units (ECU). Second, the amount of software has increased significantly due to number functions that are included in the system. In the future when machines will develop to be more automated and even autonomous the amount and complexity of the control system can be expected to increase furthermore. This is acknowledged to be a problem already at car industry.

One option for testing such system is using a Hardware-in-the-loop simulation where real control system of the machine including all the software is connected on real-time simulation model of the machine, Figure 4. In this approach test computer is feeding set of different input sequences on control system which is connected to real-time simulation computer via I/O –cards. In this manner functionality of the control system can broadly be tested and also some of the safety test can be accomplished.

Figure 4. Automatic testing of control system using real-time simulation.

Depending on content and quality of real-time simulation model of the machine, different features of the control system can be tested

- Harness
- Functionality of the software
- Tuning of control system parameters
- Behavior of automated machines

Testing of harness is not trivial due to distributed nature of the control system. However, it can be done by I/O-mapping and some auxiliary functions that are necessary for supporting communication between ECU’s.

Testing of functionality of software can be done in similar manner as harness testing if functionality of the software is described in state machine model. This testing enables finding of most logical errors which exists in control software code. Also accomplishing some safety testing may become possible in the future if safety testing standards and regulations will allow it.

If simulation model of the machine is accurate enough, it can be used for tuning of control system parameters. Generally a dynamic model is required which at the moment is challenging for hydraulically driven mechanisms.

In the case of testing of a single autonomous machine or even machine group requirements for testing becomes even more challenging due to complexity of work process and work environment. This will be especially highlighted is humans are allowed to enter to work space of a machine group.
4 DESIGN OF COCPIIT WITH VIRTUAL REALITY TECHNOLOGY

Virtual Reality (VR) technology is very promising technology for acquiring customer requirements and conceptual design because it allows exploring the design in natural size with number of people [2]. VR technology has been used in large manufacturing companies, especially relating car and aerospace industry [3], [4] despite of its high cost. However, there has been significant development in software and hardware available on market. As a result exploring 3D CAD models in VE can be accomplished with a low cost PC devices and also conversion to VR platforms is no longer problem. Applying this technology has already been subject of interest in many companies.

Virtual prototype can be studied in several displays in VE allowing its exploring with number of people, Figure 5. This enables evaluation of design alternatives at conceptual design phase between customers, engineers, industrial designers and other stakeholders. VE offers also 3D vision of the design and allows the user to move in respect to picture. This gives a very realistic feeling on moving inside a 3D picture. This realism can further be increased by haptics [5] which gives force feedback to the user and makes virtual prototype tangible.

Figure 5. Evaluation of Virtual Prototype in VE.

In spite of its realism, VE provides also inconsistent sensations which easily disturbs the user and can cause simulator sickness in more serious case. This is emphasized due to fact that in many cases such test user are at first time in VE and they have not learn to tolerate these impacts as VR professionals have. This issue has been discussed in [6] and [7]. This can at least be partially be solved by proper test arrangements. A test situation can also be improved by introducing advanced interaction techniques [8], [9], [10] such as haptic glove shown in Figure 6.

Figure 6. Evaluation of Human-Machine interface using a haptic glove.

There are interesting interactions between the actors in the triangle; Tool is loading the operator. This is generally linked with ergonomic studies. Also the operator is loading the Tool. As a result user’s different behaviour is affecting fuel consumption, machine’s productivity and lifetime of the machine. Another issue relating on this is that sometimes user’s may misuse the machine and cause unexpected loading. This is generally due to two reasons: First, users do not know how designer has taught some work to be done. Second, users are using the machine in different task or way than designer has planned. This can be studied using a virtual prototype.

Figure 7. User experience in the case of workers’ use mobile machine

Interesting interaction lies between the Operator and Outcome; Users are keen to put all their expertise on achieving a good outcome of their work. It is something that they are proud and which gives satisfaction. This important feedback is called user experience (UX) and it is considered to be very important part of products competence. Therefore its understanding is vitally important. The term UX is commonly connected to user interface design focusing on the joy to use a product, which connects the products to leisure time use [13].

This kind of experiment can be arranged in VE but for analysing the results knowledge on qualitative methods used in ethnography and anthropology is needed [14], [15], [16], [17].

In user studies of our laboratory we have made test arrangement shown in Figure 8. In the test Operator is driving
the Virtual prototype and he/she is assisted by designer or operator of the VE system. An external Observer is needed for observing how the operator is managing in different test situations. This is necessary because the designer of the system may not see the issues that are in the system that he/she has designed. Usually test group of 6-8 persons is adequate for the test.

For the understanding the emotions related driving to the machine a motion platform is connected to real-time simulation model and visualization as shown in Figure 9.

5 SUMMARY

Development and testing of Mobile machines will increasing be made with product models, real-time-simulation and Hardware-in-the-loop simulation. This due to both increased complexity of machines as well as shortened design time. Especially testing of control systems of autonomous machines and machine groups will be complex. Importance of Conceptual design phase can be extended with VR-tools and User testing. This supports construction of mobile work machines with good user experience. Design of Mobile Work Machines will increasingly take place in Cyber Space.

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Proposal of 3D Micro Prototyping Using Synchrotron Radiation and Its Application to Bio-Microsystems

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Abstract
A new X-ray microfabrication system and succeeding molding process as the 3D micro prototyping process have been developed using synchrotron radiation (SR) lithography and nano-imprinting technique. We adapted the process to the achievement of 3D microfluidic platforms for bio chemical applications which will be used point-of-care diagnostics and drug compound screenings. An enzyme linked immunosorbent assay method has been applied to the analysis of the endocrine disrupter using proposed fluidic platforms. Drastic improvement of the analysis sensitivity and decreasing of the total analysis effort and required time have confirmed

Keywords:
synchrotron radiation; microfabrication; microfluidics; Lab on chip; assay; ELISA; DNA

1 INTRODUCTION
There have been rapid developments in the application of microsystems in advanced industries such as intelligent information systems, energy and environment conservations, and medical and biochemical applications. Microsystems typically consist of different types of precise parts for various micro structures. The realization of 3D microstructures integrating multiple functions, such as electrical, optical, mechanical, and chemical sequential operations, in a restricted space will bring many advantages to the industry development. Systems of this type have been fabricated using micro-electro-mechanical system (MEMS) processes. Recently, however, fabrication techniques with a higher precision and a higher aspect ratio than those conventionally achievable have become increasingly important. This is due to the fact that natural phenomena on which these device functions are based, such as electrostatic fields, surface tension, and surface chemical reactions, tend to become more pronounced as specific surface area increases. To realize these requirement, we developed a new “3D micro prototyping process” based on X-ray microfabrication system equipped at the “NewSUBARU” SR facility [1,2], and succeeding molding process using synchrotron radiation (SR) lithography and nano-imprinting technique. The stacking process as the device packaging of obtained micro structures is more essential where it needs various surface treatment and succeeding bonding process with different materials [3,4]. Meanwhile, the progress of life science has been increasing rapidly and the development of the platform technologies that supports it become more significant. Miniaturization and integration technology that have been successfully developed at microelectronics fields are nowadays adapting also to automated chemical analysis and synthesis, based on miniaturized total chemical system, so-called “μTAS” or “Lab on Chip” made from microfluidic components. We adapted proposed “3D micro prototyping process” to the achievement of the integrated microfluidic platform and have confirmed advantages of 3D micro-integration of chemical functions in one platform for some biochemical applications. A high sensitive and rapid enzyme linked immunosorbent assay (ELISA) method are demonstrated using micro 3D-structured system consists of 3D microfluidic channel network and vertical chemical operation chamber with fluid control filter and mixer. Drastic improvement of the analysis sensitivity and decreasing the total analysis effort and required time have found in the applications to the environmental analysis and DNA analysis.

2 3D MICRO PROTOTYPING USING SYNCHROTRON RADIATION

2.1 3D X-ray Microfabrication System
The “lithographie, galvaniformung, abformung” (LIGA) process, which consists of deep-X-ray lithography, electroforming, and molding, is a promising candidate for 3D microfabrication[5]. The LIGA process starts from the fabrication of high-aspect-ratio polymer microstructures with heights greater than a few hundred microns using deep-X-ray lithography of a photosensitive polymer (resist) [6]. In the next step, a metal replica structure is formed by electroforming using the fabricated polymer master. The obtained metal replica structure can be used as a component in a

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Figure 1: Schematic diagram of newly developed lithography system using SR.
microsystem or as a mold insert for final molding processes, such as hot embossing and injection molding. It is important to develop a next-generation process that can achieve both a large process area and more fine fabrication property simultaneously. No such process satisfying the demands has yet been realized. We established a new X-ray lithography system, “BL2”, with a large exposure area of up to A4 size, developed at the “NewSUBARU” synchrotron radiation facility [2]. Figure 1 shows a schematic diagram of the newly developed apparatus for lithography. It consists of a beamline with X-ray optics for energy selection and an exposure apparatus with multi motion stages. The main feature of our lithography system is that it can continuously select X-rays from 1 to 12 keV using mirrors and the filters. Each energy region can be selected in accordance with the desired size and shape of the fabricated microstructures. Figure 2 shows the relationship between the processing depth of a PMMA resist after 3 h of development and the X-ray exposure dose at operation energies of 1.0 and 1.5 GeV. A processing depth of more than 1600 µm was obtained with exposure to the high-energy X-ray beam during 1.5 GeV operation. It is clearly shown that exposure photon energy changes dose dependence on processing depth of the work (PMMA), since the penetration depth of the X-rays into the resist varies according to their energy. By scanning the 210-mm-wide SR beam along the longitudinal axis with a 800 mm span, full A4-size exposure can be achieved. Figure 3 shows that large-area patterning of an area of 220 mm × 300 mm (A4-size) with a highly uniform pattern thickness is successfully demonstrated using this system. The uniformity of the pattern thickness along the horizontal direction was estimated to be less than 5%. Patterning with an aspect ratio greater than 20 was confirmed. Using this large-area X-ray lithography system, high-aspect-ratio microstructures with a wide range of sizes, from submicron to millimeter, can be achieved by using different type of X-ray masks in the same exposure chamber. In order to apply this system to the fabrication of advanced microsystems with more integrated functions for automated operations, it is necessary to develop a high-precision 3D microfabrication technique capable of sizes less than several dozen of microns. Several 3D microfabrication studies have been reported so far [7-8]. In this study, three-dimensional microstructures can be obtained by exposing the X-ray beam intermittently over work substrate (PMMA) with different incident SR angles set by multi axis stages [9] as shown in Figure 4 (a), (b). This structure shows the cross-linked micro capillaries for mixing of micro fluids with small Reynolds number, where high mixing efficiency was confirmed from the reaction speed measurement of the enzyme and substrate solution [10]. This 3D structure of cross-linked micro capillaries can be fabricated by tilting the exposure stage. The 400µm thick PMMA sheet and X-ray mask are mounted on an X-ray exposure stage, and the stage is tilted from the vertical axis, and PMMA sheet is exposed to X-ray. Then, the stage is reversely tilted by same angle and exposed again. The distance between crossing axes of the capillaries can be controlled by rotating the X-ray mask a few degrees. The mixing efficiency was significantly affected by the distance between center axes of each capillary. Figure 5 shows the results of the computational fluid dynamics (CFD) simulation of water mixed after 0.5 ms, which suggests the great improvement of the mixing efficiency by using this 3D structured capillaries. The color bar indicates mass fraction of the colored water. Figure 5 (b) shows time shift of standard deviation of the mass fraction of the ideal separated waters inquired from both side of the two cross-linked capillaries and mixed in capillaries as the mixing progress. The capillary structural parameter is 40 µm and 400µm in diameter and length. The result shows that mixing efficiency in cross-linked capillary is much increased at the structure of which distance between center axes of each capillary is half in diameter (half cross-linked structure). Moreover, the mixing will be finished within 1 ms by the use of the mixer with half cross-linked micro capillaries.

Figure 2: Exposure-dose dependence of processing depth. Circles show the data using the high-energy spectrum for 1.5 GeV operation. Squares show the data using the low-energy spectrum for 1.0 GeV operation.

Figure 3: PMMA resist patterns fabricated using large-area deep x-ray lithography system. A4-size deep x-ray lithography, and right magnified image shows patterns with high accuracy.

Figure 4: (a): Three-dimensional microstructures patterned on a 400 micron PMMA sheet using SR with multi step exposure. (b): magnified image of the cross-linked micro capillaries.
2.2 Microfabrication of PTFE by SR-induced Direct Etching

The X-ray microfabrication system can also apply the SR-induced photo-chemical reaction to direct etching of fluorinated polymer molecules such as polytetrafluoroethylene (PTFE) and polytetrafluoroethylene-co-perfluoroalkoxy vinyl ether [11-12]. PTFE has big potential for various applications, such as chemical, bioscience, electronics and environmental applications, for its electrical, chemical, mechanical and thermal properties. Due to its property microfabrication of PTFE with high precision has been difficult so far by the use of conventional machining, molding, and semiconductor processes. In order to accomplish wider practical applications of PTFE, microfabrication with large work-area is inevitable. We have demonstrated the PTFE microfabrication using the developed X-ray Microfabrication System and investigated the processing characteristics of PTFE direct etching.

At the first step, processing characteristics of the PTFE direct etching using SR had been studied. In the experiments, relatively high-energy region of 2 to 6 keV and 2 to over 10 keV were used at the condition of storage electron-beam energy of 1.0GeV and 1.5GeV, respectively. To investigate heating effects during X-ray exposure, large-area hotplate was mounted onto the stage and PTFE substrates, which cleaned with methanol, were attached on the hotplate to face the X-ray beam. Figure 6 shows For the lower dose of 55 mA-hr the irradiated surface shows very smooth and fine morphology. On the contrary, there were found bubble-like structures at the higher dose of 165 mA-hr. The morphology is closely related to the etching mechanism as speculated below. As shown in Figure 7, it can be speculated that melting of PTFE less than original melting point occurs by SR irradiation, because high energy soft-x-ray photons induce continuous decomposition of PTFE. The volatile decomposed fragments of PTFE desorb from the SR-irradiated surfaces(Fig. 7(a)). As x-rays penetrate into PTFE substrate deeply, the bond-brake progresses in deeper part of the substrate. Furthermore, as elevated heat Figure 7: Speculated mechanism of PTFE etching; (a) PTFE decomposition, fragment desorption and decrease of melting point, (b) formation of melting block at the SR-irradiated area, (c) growth of the bubbles in melting block, (d) continuous etching of melting block by SR-induced reaction and thermal desorption, (e) finish of PTFE etching at SR-irradiated area.

Figure 8: Etching rate dependence on substrate temperature.
Y. Utsumi

contributes to rapid diffusion of decomposed PTFE molecules, it leads to the formation of large melting block expanding in entire exposed aria (Fig. 7(b)). This melting of PTFE was supposed to result in the abrupt rate increase around 165 degrees as shown in Figure 8. Decomposed fragments will agglutinated and results in the growth of the bubbles in melting block (Fig. 7(c)). Etching of melting block by SR-induced reaction and thermal desorption continuously progresses during these steps and finally the irradiated part will be selectively etched (Fig. 7(d,e)). By these processes, PTFE will be precisely etched by the use of developed lithography system.

Next, the PTFE micro capillaries filters with functions as microvalve, micromixer, and microreactor, were fabricated. Figure 9 is SEM images of fabricated PTFE filter with about two thousand arrayed micro capillaries. The thicknesses and capillaty diameter are ranging from 130 to 2000 µm and 25 to 40 µm, respectively so the maximum aspect ratio of capillary was 80. Patterning to A5 size PTFE sheet using wet-etched stencil mask was also demonstrated. It is useable for large-area microstructure applications such as lab-on-a-chip devices for medical and environmental high throughput analysis.

Figure 9: SEM images of fabricated PTFE filter with about two thousand arrayed micro capillaries.

2.3 Stacking of Microstructure using Direct Bonding and Nanoimprint Technique

The next process following after deep x-ray lithography, molding process was investigated using nanoimprint technique. Figure 10 shows the SEM images of the microchannel structure of micro capillary electrophoresis (MCE) chip for DNA analysis formed after molding of PMMA sheet by nanoimprint apparatus. The accuracy of the line dimension was less than 4% from the nickel mold inserts. And the surface roughness of the micro channel wall was less than few nm, which show the enough precision for assembly the whole DNA chip structure with multiple functions. In order to achieve the microsystem with desired functions, the assembly of the individual micro parts is inevitable. We have attained the assembly of the plastic micro parts by the use of the direct fusion bonding using nanoimprint apparatus to press the stacked molded structures in head loads. The fusion bonding without binding agent is necessary to avoid the inclusion of the binding agent into the micro fluid channel and to attain the dimension accuracy, which is degraded by the insertion of binding layer with low thickness stability. The fusion bonding of each three PMMA layer; top layer of a sample injection, second electrodes layer for DNA amplification and separation with 96 MCE units, and bottom heat exchanger layer, was demonstrated after some treatments of the bonding surface. Figure 11 shows the result of the trials for fusion bonding of two PMMA layers at different temperature and bonding time. The cross sectional SEM images as shown in Figure 12(a) shows the sealed microchannel with no defects and air bubble at the sealed interface and Figure 12 (b) shows the whole outside view of the stacked structure of chip with 96 MCE units for DNA analysis, which size is 88mm x 130 mm[13].

3 APPLICATION TO BIO MICORSYSTEMS

3.1 Proposal of Bio Microreactor with Vertical Chemical Operation

The automation of bio-operations has became a key subject to realize point-of-care (POC) diagnostics and high throughput screenings (HTS) of various matters, such as medicine, DNA, proteins in post-genome analysis, products from immunoassays. From this point of view, "Lab on Chip" system, on which multiple chemical operations are sequentially performed through microfluidic components have been
Proposal of 3D Micro Prototyping Using Synchrotron Radiation and Its Application to Bio-Microsystems

attracted great attentions, because of their leading features such as compactness, small sample volume, fast and precisely controlled reaction, high analysis sensitivity, shortage of required time, reproducibility of output data, and low cost reliance. Such properties originated from down sizing of fluidic channels and components integrated monolithically which results in a large surface-area-to-volume ratio, a rapid thermal diffusion, a high pressure gradient, a high reagent solution concentration, and a mechanical toughness. However, typical structure of the conventional “Lab on Chip” systems assembled on a two-dimensional planar substrate has restrictions of integration of every fluidic components necessary for attaining whole sequential chemical operations specified in an analysis and synthesis.

Achieving 3D integration of multiple chemical modules and these interconnections within a finite small space will results in the integration of multiple functions which composes total sequential chemical operation, and will develop several major application fields, such as POC diagnostics, HTS of the matters, fine chemical synthesis, combinatorial synthesis.

As the first step to achieve 3D integration of microfluidics, we proposed and fabricated a new chemical reactor with a vertical fluid flow operation. As shown in Figure 13, the reactor utilizes fluid filter in which thousands of micro-through-bores...
Electrophoresis have been well developed, however the micro-sensitivity (5-100 ng/ml) obtained by ordinary ELISA using NP was obtained at the range of 0.01-10 ng/ml as shown in Figure 17. This sensitivity was two orders higher than the ordinary ELISA using anti-NP-antibody immobilized on surface of the micro-through-bores, at which immuno-binding (B/B₀ = 90%). Whole analysis protocol have been performed using automatically operating system (ELISA), which enable highly sensitive detection of an endocrine disrupter (nonylphenol) by a series of vertical fluidic operation. In this analysis, competition between nonylphenol and nonylphenol-Horseradish-peroxidase conjugate occurs at the binding of these molecules to anti-nonylphenol monoclonal antibody (anti-NP-antibody) immobilized on surface of the micro through bores as shown in Figure 9. In the assay using filters pretreated with 0.3 μg/ml of anti-NP-antibody, even at 0.01 ng/ml of free NP, we still observed the inhibition of the binding (B/B₀ = 90%). Whole analysis protocol have been performed using automatically operated system shown in Figure 15. Under this condition, calibration curve of NP was obtained at the range of 0.01-10 ng/ml as shown in Figure 16. This sensitivity was two orders higher than the sensitivity (5-100 ng/ml) obtained by ordinary ELISA using 96-wells micro-titer plate and the same anti-NP-antibody. These assays gave reproducible results, reactor to set at the centers of the filters.[14-15].

3.2 3D Micro Fluidic Network

The miniaturized analysis chip such as microchip electrophoresis have been well developed, however the micro-

chemical systems with whole bio-chemical processes, including sample pre-treatment, have not been developed, while it requires much efforts and time over separation and detection. The key-technology for the solution is assembly and interconnection technologies because seamless functional connection of various devices is necessary to achieve totally automated microchip systems. The various chemical operations must be realized on one platform to realize totally automated bio-process. We adapted proposed “3D micro prototyping process” to the achievement of such advanced systems and have confirmed the advantages of 3D micro-integration of chemical functions in one chip for DNA analysis and some immunoassay applications. We proposed 3D fluidic platform system in which total chemical unit operation necessary to achieve without human operations can perform automatically, which brings high analysis sensitivity and less total analysis effort and required time. In this concept whole procedure for immunoassay can be achievable by stacking multiple CD fluids with individual functions corresponds to each sequential step for bio-chemical operation to cover whole procedure for assay. This concept is shown as the schematic diagram of a new CD-like microfluidic platform with 3D fluid networks in Figure 17. In this system only necessary manual operation is loading of sample and reagent solutions into inlets. The analysis processes typically start with this sample purification followed by some sample preparation dilution and amplification. The purified samples are then mixed with buffer solutions containing another regents such as enzyme-labelled haptens by increasing the rotation speed of CD. The regents are pre-loaded in the other chamber formed on the bottom disk of the stack structure. The specific volumes of regent solutions and sample liquids are automatically injected into mixing chamber located in the middle disk of the stacked structure consists of three-dimensionally crossing channel network, and dispensed to desired volume ratios for designed protocol. For complete mixing of sample and regents the high-efficiency mixing device is necessary. For this purpose a 3D mixer with opposed-capillary structure is feasible at the mixing chamber. The mixture will next injected into biochemical reaction chamber with antibody immobilized 3D microstructure. Specific area of immobilized antibody become to be several decades times larger than conventional planar reactor microchannels, which results in the enhancement of the reaction rate and the analysis sensitivity, reproducibility of the immuno systems. The solution of product of bio-chemical reaction will then injected into detection chamber located after the reaction chamber and amount of the product will measured by using optical detection. Normally, optical path of micro channel on a conventional planar fluidic platform, which corresponds to the depth of the fluidic channel, is less than 100 micron and it has restrictions for detection such as difficulty of alignment and small signal due to the lack of optical path for absorption and fluorescence detection. On the other hand stacked CD structure can increase optical path up to several millimetres by forming detection channel across the stacked CDs.

Figure 17: Schematic diagram of a new CD-like microfluidic platform with 3D fluid networks.
One promising way to realize automation for immunoassay is to utilize CD-like microfluidic platforms as mentioned above. In this section we will describe the detailed structure and protocol for ELISA with high-sensitive and high-speed, and high-reliable property of 3D CD platform devices. For automatic ELISA, the liquids, sample, wash, substrate, and reaction aborting solution are pre-loaded into reservoirs and sequentially injected into 3D bio-reaction chamber by spinning CD. For the first sequencing, the mixture of sample and enzyme conjugated hapten will be injected and competitively conjugate with 1st antibody immobilized on the surface of 3D microstructure. After incubation, the washing buffer will injected from second reservoirs by accelerating hundreds rpm, and excess samples will be washed away. The next, substrate reagent to quantify the extent of competitive reaction of sample and enzyme labelled haptns will be injected from third reservoir into reaction chamber and incubated to amplify the signal of products according to designed protocol. Finally the enzyme reaction will stopped by injecting reaction stopping solution released from fourth reservoir, and amount of products will measured in optical chamber and calibration curve will obtained. Figure 18 shows illustration and photographs of designed and fabricated devices. The devices consist of three-stacked layers with ten assay units for parallel assay of 10 samples. Each unit consists of four liquid loading reservoirs and biochemical chamber with filter structure as mentioned at chapter 3.1 and optical detection chamber. All CDs are aligned and stacked together by using self-adhesion of poly-dimethylsiloxane (PDMS). The thickness of the reservoirs and chambers set to adjust the suitable sample, reagent volumes and optical path length of the reaction products for UV absorption and fluorescence. The high aspect ratio structure of liquid loading reservoir is effective to integrate assay units by reducing planar area of reservoirs. To demonstrate the automatic sequencing in 3D CD platform, we loaded protein solution into the reservoirs (0.1% bovine serum albumin phosphate buffer solution: 0.1%BSA) and CD platform is spun for the sequencing. The snapshot images are obtained by strobe scope system to observe and measure the burst frequency of each chamber. The schematic illustration of strobe scope system is shown in Figure 19. The optical sensor will generate
the trigger signals for the synchronized control of CCD and strobe. The taken images are automatically grabbed with time information into PC and burst frequency was calculated by checking holding state and the time.

Figure 15 (a) show the obtained images of automatic flow sequencing in 3D CD platform and measured burst frequencies are shown in Figure 20 (b). As shown in Figure 20 (b) we succeeded in sequential transportation of BSA solution in four individual reactor units in 3D CD-like platforms. The result suggests the proposed 3D microfluidics platform is available to automated ELISA analysis.

4 SUMMARY

3D micro prototyping process have been developed using synchrotron radiation (SR) lithography and nano-imprinting technique. Large-area patterning up to A4-size area was also successfully performed with a highly uniform pattern thickness. The X-ray microfabrication system can also apply the SR-induced photo-chemical reaction to direct etching of fluorinated polymer molecules. The stacking process as the device assembly and interconnections for obtained micro structures is also demonstrated using some types of surface treatment and succeeding nano-imprinting techniques for assembling 3D functional fluidic structure. We adapted proposed “3D micro prototyping process” to the achievement of 3D micro fluidic platforms and have confirmed the novel properties of high analysis sensitivity, speed, and low reagent consumption. For some assay applications, an enzyme linked immunosorbent assay method has been investigated using proposed micro 3D fluidic platforms in which thousands of micro capillary are integrated as a fluid control filter and bio-chemical reaction space in 3D fluid networks. Drastic improvement of the analysis sensitivity and decreasing the total analysis effort and required time have found in the applications for the environmental analysis. We also succeeded in sequential transportation of BSA solution in four individual reactor units in 3D CD-like platforms.

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6 REFERENCES

Surgical Tool Based Preoperative Planning System for Total Hip Arthroplasty

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Abstract
In preoperative planning of total hip arthroplasty, a type, a size and a place of a femoral stem is planned on plane radiographs or computed tomography images. However, the shape of the natural medullary cavity of the femur on these images differs from a prepared one expanded with reamers and rasps to insert the stem. This difference makes it hard to select an appropriate stem and its position without imagining behavior of surgical tools. In this paper, we propose a surgical tool based preoperative planning system for total hip arthroplasty to obtain a minimally invasive position of the stem.

Keywords:
Total hip arthroplasty; Preoperative planning; Minimally invasive surgery

1 INTRODUCTION
Appropriate selection and placement of a femoral stem lead to a good surgical result. The femoral stem which does not suit patient’s femur causes leg length discrepancy and shortens the longevity of the artificial hip joint. Even if a surgeon found that the selected femoral stem is not fit the femur during the operation, reselecting another femoral stem prolongs operation time to increase the burden for patients and risk of infectious disease.

In the preoperative planning of total hip arthroplasty (THA), the surgeon selects the femoral stem subjectively. A type, a size and a place of the femoral stem is planned on plane radiographs or computed tomography (CT) images. A template of the femoral stem is placed on these images to find an appropriate position of the femoral stem referring to a shape of the medullary cavity. There are some studies to find the optimal position of the femoral stem automatically [1][2], but there is still no gold standard except the surgeon’s experiences.

The shape of the medullary cavity of femur is also determined by the surgeon subjectively. The shape of the natural medullary cavity is given as a contoured one with a certain threshold of Hounsfield Unit (HU). The surgeon imagines the contour of the medullary cavity on plane radiographs or sets proper HU to shape one on a preoperative planning system. This procedure is called as segmentation, and there are some attempts to make segmented bone model objectively, but automatic segmentation is not still free from the surgeon’s experiences [3].

In this paper, we present a novel method to determine the position of the femoral stem objectively by predicting the shaped medullary cavity of the femur. The femoral stem is inserted into a medullary cavity of femur after the surgeon expands the medullary cavity with surgical tools such as reamers and rasps. This prepared shape of the medullary cavity differs from the natural shape of one. The surgical tools are designed to shape the medullary cavity into a little smaller shape of the femoral stem. Predicting the prepared shape of the medullary cavity, the position of the femoral stem could be determined properly. Thus, our goal is simulating behavior of the surgical tools as a preoperative planning system of THA to obtain the appropriate position of the stem.

The expert surgeon pays attention not to hurt cortical bone with the tools while expanding the medullary cavity [4]. This prepared medullary cavity could be regarded as a minimally invasive shape for inserting the femoral stem. In order to simulate this surgical technique, we introduce an evaluation function, Invasive Parameter (IP) to estimate damage to femur. IP has been given as a sum of squares of the apparent densities of bone’s elements which will be destroyed by the surgical tools. By minimizing IP, we could get an optimal position of the femoral stem. This proposed algorithm needs no segmentation process. Efficiency of proposed method is evaluated on the real CT images.

2 PREPARING THE MEDULLARY CAVITY OF FEMUR
In a surgical operation, the medullary cavity of the femur is expanded with reamers and rasps as shown in Figure 1(a). The reamers dig in the longitudinal direction of femur to form the axis of the femur. Then, the rasps shave the medullary cavity along with the femoral axis for preparing the stem insertion. Because the shapes of the rasps are rather smaller ones of the femoral stem, the shape of prepared medullary cavity would be ready for insertion of the femoral stem.

In the proposed preoperative planning system, the surgical operation which shapes the medullary cavity of the femur is simulated on real CT images as shown in Figure 1(b). In the simulator, CT images are used as are, and would not be segmented. Pixels would be removed by segmentation are used for calculating IP. A procedure of the simulator is following. (1) The femoral axis is determined by simulating behavior of the reamers minimizing IP. (2) Inserting the rasp along with the femoral axis rotating around the axis to find the...
position with minimal IP. Finally, the position of the optimal position of the femoral stem is given as one of the final rasp.

Figure 1: Preparing a shape of a medullary cavity of femur.

3 ESTIMATING INVASIVENESS

3.1 A Model of the femur

Before explaining about IP, the model of femur for the proposed simulation is to be described. The femur is modelled as several slices of CT images as shown in Figure 2. Each CT slice has zero thick and placed referring to its DICOM header. Ordinarily, voxels are used in the field of visualization and analysis of medical data, however handling CT images as voxels increases calculating time for collision detection and errors cased by similar reason to the partial volume effect. A collision between the bone and the tool is detected by simply finding the pixels inside of the models of the surgical tools.

3.2 Invasive Parameter (IP)

The reamers and rasps are operated according to not only the preoperative plan, but also the reaction force through the tools in the operation. The tool working as a probe allows the expert surgeon to decrease invasiveness while expanding the medullary cavity. Invasive Parameter: IP is introduced to estimate the reaction force through the tools. IP has been given as following.

\[
IP = k \sum_{i=1}^{n_{CT}} \sum_{j=1}^{n_{pixel}} (HU_{ij})^2, 
\]

where,
- \( k \) is constant can be 1 here,
- \( n_{CT} \) is number of CT images,
- \( n_{pixel} \) is number of the pixels interfering the tool
- \( HU_{ij} \) is Hounsfield Units (HU) of the pixels

\( (HU_{ij} = 0 \text{ if } HU_{ij} < 0 \text{ here}) \)

The reaction force is regarded as being proportionate to a sum of compressive strength of each element of the bone is to be removed by the tool. The compressive strength can be assumed to be proportionate to the square of the bone density [6]. Thus, IP is proportionate to a sum of the squared HU of the each pixel in the CT images. A minimally invasive position of the tool is estimated by minimizing IP.

4 REAMING SIMULATION

4.1 A model of the reamer

In THA, tapered reamers are used to expand the medullary cavity of femur. In the reaming simulator, the reamer is modelled as a cylinder to ignore the depths of insertion of the reamer to simplify the model. A schematic diagram of the reaming simulation is shown in Figure 3. A diameter of the reamer starts from 1mm and increased by 1mm to 7mm in this evaluation.

Figure 2: A model for calculating invasiveness.
IP is calculated and compared with ones of the neighbours to find the position with minimal IP. When the reamer reaches the position with minimal IP, elements of femur interfering in the reamer is removed, in other words, all HU of the pixels being interfered with the reamer are set to zero. Then, the diameter of the reamer is increased and the reamer finds the minimal IP position to the maximum size of the reamer. We have used real CT images provided by VAKHUM project [7] for the evaluation. Table 1 shows the conditions of an evaluation of the simulation.

Table 1: Conditions of the real CT images.

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<table>
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<tbody>
<tr>
<td>Number of CT images</td>
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<tr>
<td>Pixel spacing of CT image [mm]</td>
<td>0.84 x 0.84</td>
</tr>
<tr>
<td>Space between each slices [mm]</td>
<td>1 (proximal part) 3 (distal part)</td>
</tr>
<tr>
<td>Size of CT image [in pixels]</td>
<td>512 x 512</td>
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4.2 Result of the Reaming Simulation
The reamer was initially placed inside of the medullary cavity arbitrary. In all cases, the reamer had been converged on an unique position finally.

Figure 4 shows the result of the reaming simulation. The validity of proposed method has been confirmed visually. The result suggests the possibility of automated determination of the femoral axis. A calculation time for a convergence was within 12 seconds with Intel Core™ 2 Duo E6600 (2.4GHz, with one thread).

In order to confirm the convergence of IP with the reaming simulation, IP around the minimally invasive position was obtained at each position of the reamer. Figure 5 shows that IP changes rapidly according to the translation of the reamer, which indicates strong convergence of IP, and suggests the robustness of the proposed algorithm.

5 RASPING SIMULATION
5.1 A model of the rasp
The shape of the rasp for THA has similar shape of the femoral stem with rather small size. The rasps are designed for each femoral stem to prepare the medullary cavity of femur for inserting the stem. The rasp expands the reamed medullary cavity of femur to fit the shape of the femoral stem. In the rasping simulation, the shape of the raps is modelled as a parametric shape as shown in Figure 6. Using parametric shape make it possible to reduce calculation time.
for detecting collisions. The rasp model moves in two degrees of freedom. One is translation along with the femoral axis determined by the rasping simulation, and the other is rotation around the femoral axis. These two movements simulate the insertion of the rasp and the behavior to seek an appropriate angle of the rasp with feeling the reaction force through it in the real surgical operation.

5.2 Result of the rasping simulation
A rasping simulation was performed after the reaming simulation. Appropriate rotation angle of the rasp with minimal IP was determined by setting the depth of insertion to 55mm. Here, this depth is determined by an operator subjectively referring CT image and the shape of the rasp. As mentioned later in discussion; section 6.3, proper depth of insertion could not be determined by just comparing IPs. Then, the rasp rotated from 0 degree and increased by 1 degree to 360 degree. The result of the rasping simulation is shown in Figure 7. The final position of the rasp seems to fit the medullary cavity well to the eye. A calculation time for a convergence was within 70 seconds with Intel Core™ 2 Duo E6600 (2.4GHz, with one thread).

In order to confirm the result objectively, the convergence of IP has been considered numerically. IP was calculated according to the changes of the depth of insertion and the rotation around the femoral axis as shown in Figure 8. IP increases according to the depth of insertion. There are a few local minimums of IP observed when the rasp was not inserted deeply. However by inserting the rasp deeply, an unique minimal IP indicated by an arrow sign in the Figure 8 can be obtained. The position of the rasp on Figure 7 is the position with this minimal IP. Because the shapes of the medullary cavity and the rasp have the same morphological characteristics such as swelling in one side, it’s natural that there is a point with such minimal IP. The result suggests the possibility of automated placement of the rasp, and the femoral stem.

6 DISCUSSION
6.1 Segmentation or surgical tool based shaping
Conventional preoperative planning systems for THA need segmentation to operate a medullary cavity of femur and a femoral stem. These systems handle a task to place the femoral stem as one of contact problem. To solve a contact problem, two or more different surfaces, their physical properties are needed. In the case of THA, two surfaces are
the shapes of a medullary cavity of femur and a femoral stem. The shape of the femoral stem is known, but the shape of the medullary cavity is ambiguous. Here is an example as shown in Figure 9, the shape of the medullary cavity changes depending on a threshold value of HU. There are three cases of thresholds and contours created by converting pixels of CT images into binary value at each threshold. Contours on Figure 9 explain difficulty of making shape of the medullary cavity of femur property. So, conventional approaches are not free from current gold standard of determining threshold, which is made by the expert surgeon. There are yet another complicated problems with physical properties, we never mention about them here.

Our proposed algorithm does not need segmentation, so that this approach is free from a contact problem. This algorithm handles the medullary cavity and the surgical tools as solid rigid bodies. Only relative strength of each element of the bone is needed for simulating behavior of surgical tools. Searching a position with minimal IP leads the surgical tool model to the optimal position. Here, ‘optimal’ means having least invasive to the bone.

6.2 Calculating time with a proposed algorithm
This proposed algorithm brings rapid results. Medical data tend to be handled as voxels or meshes for the reason of visualization or the restriction of the application software. Detecting collision between voxels or meshes requires long time to calculate. In the proposed algorithm, CT image is handled as groups of pixels, and the surgical tool is described in a parametric manner to reduce calculating time. Of course, the surgical tools can be described in polygons such as a STL format, which would not increase calculation time too much.

6.3 Using this algorithm in preoperative planning
Predicted prepared shape of the medullary cavity of femur is almost the same shape of the inserted femoral stem, so that the proposed algorithm could be used for preoperative planning of THA. To use this algorithm clinically, the limit of IP should be determined to stop the insertion of the rasp. The rotation of the rasp can be determined minimizing IP as shown in Figure 8, while there is no mean to determine the proper depth of the insertion of the rasp. The limit of insertion could not be determined by merely comparing IPs. The limit of the insertion would be determined comparing the results of the simulations with clinical results.

7 CONCLUSIONS
Conclusions are summarized by the followings,
1) A novel algorithm for preoperative planning for THA has been proposed, which could place the femoral stem in the medullary cavity of femur at an unique position automatically.
2) A prepared shape of the medullary cavity shaped by surgical tools has been predicted uniquely with strong convergence of IP, which suggests the robustness of the proposed algorithm.
3) A prepared shape of the medullary cavity composed of 108 of CT images formed by the reaming and rasping simulator within 80 seconds with the proposed algorithm with Intel Core™ 2 Duo E6600 (2.4GHz, with one thread).

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9 REFERENCES


A Trial of Numerical Calculation of Wear for Artificial Hip Joints

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Abstract
A numerical analysis method for the wear of the artificial hip joints due to the walking is proposed and a wear prediction system for them is developed in this research. In order to develop the system, EHL, “elasto-hydrodynamic lubrication theory” and a model for asperity load sharing are applied. The feasibility of the developed wear prediction system for artificial hip joints is shown and the relationship between the wear and various parameters of the artificial hip joint is described in this paper.

Keywords:
Artificial hip joint ; Elasto-hydrodynamic lubrication ; Wear ; Lubricating film thickness

1 INTRODUCTION
Total hip replacement is often used to treat joint failure caused by osteoarthritis. The life span of artificial hip joints is about 20 years; hence some attempts related to stress analyses, material developments, manufacturing methods, surface treatment methods and wear analyses have been conducted in order to extend the their life time. Especially, the wear deteriorates functions of the hip joint, and the wear-particle induces osteolysis mediated aseptic loosing [1].

Regarding the wear and the lubricant analysis models, some researches has been carried out for artificial joints. Wearindex is applied to predict the wear for the artificial knee joint [2]. This method is very simple to use, but this doesn't include all parameters of the artificial joint. Hence, the analyzed results can’t be used for some artificial joints design. The lubricant model for the artificial hip joints has been proposed [3, 4] based on Elasto-hydrodynamic lubrication (hereinafter EHL). This method is suitable for the analysis for the distribution of the pressure and the lubricant status with considering the parameters related to the artificial hip joint. This isn't, however, suitable for the wear prediction, because the asperity contact can't be considered.

In this research, a numerical analysis method for the wear of the artificial hip joints due to the walking is proposed and a wear prediction system for them is developed based on EHL theory. The novel aspect of this research is to realize the wear calculation with consideration of the detailed lubrication status of the artificial hip joint due to the dynamic change during one walking cycle. By using the wear prediction system, the artificial hip joint of metal-on-metal type is analyzed in this paper.

2 WEAR PREDICTION SYSTEM FOR ARTIFICIAL HIP JOINTS
2.1 System Overview
There are three lubrication status: hydrodynamic, boundary and mixed lubrication [5] as shown in Figure 1. The lubricating film supports the load in the hydrodynamic lubrication, hence the wear hardly occurs. The bodies come into closer contact at their asperities in the boundary lubrication, hence The plenty of wear occurs. The mixed lubrication means the intermediate condition between the boundary and the hydrodynamic lubrications.

In order to estimate the wear, the lubrication status should be distinguished properly. Hence, the we construct a prediction system with considering the aforementioned problem.

Figure 1: Stribeck curve and lubricantion status.

Figure 2: System overview of wear prediction system.
The wear prediction system developed in this research consists of four blocks: a model generation, a load calculation, a wear calculation and a walking database blocks as shown in Figure 2.

The model generation block generates an analysis model for the micro-geometry of the contact, when a cup and a head radii of a femoral component, an equivalent RMS (Root Mean Square) surface roughness, an asperity density, an equivalent Young's modulus, an asperity radius, a lubricant pressure coefficient, a lubricant viscosity, a wear coefficient and a body weight are input to the system.

The load calculation block calculates each load on asperities and the lubricating film. In order to obtain the each load, a minimum lubricating film thickness is estimated based on “elasto-hydrodynamic lubrication theory”, which considers the elastic deformation of the lubricating surface due to the pressure. The each load is determined from the obtained minimum lubricating film thickness.

The wear calculation block calculates the wear of the artificial hip joint due to the walking with consideration of the load on each asperity and the lubricating film. The walking database block stores a change of the hip joint angle during one walking cycle and a joint force per body weight. The change of the hip joint angle during one walking cycle is used to calculate the velocity of the sliding surfaces between the cup and the head of the femoral component, and the joint force per body weight is used to calculate the two kinds of loads on each asperity and the lubricating film.

2.2 Model generation block

It is assumed that a mixed lubrication status is occurred between a cup and a femoral head shown in Figure 3. This means that two surfaces are separated by a gap distance. Then, there is a lubricant film and are some asperities to share the total load.

\[
\frac{1}{B} = \frac{1}{R_1} + \frac{1}{R_2} \quad (1)
\]

\[
\sigma_1^2 + \sigma_2^2 = \sigma^2 \quad (2)
\]

In order to calculate two kinds of load on each asperity and the lubricant film theoretically, a contact between two surfaces are regarded as the one of a cylinder and a flat surfaces shown in Figure 4. Then, an equivalent radius, B, and an equivalent RMS surface roughness \( \sigma \) of the flat surface are obtained by the following equations.

In equation (1), \( R_1 \) and \( R_2 \) mean the radii of a cup and a femoral head, respectively. Plus and Minus signs also correspond to Figure 5.

In equation (2), \( \sigma_1 \) and \( \sigma_2 \) mean the RMS surface roughness of each surface, respectively. In the Figure 4, \( u_1 \) and \( u_2 \) also mean the sliding velocities of each surface, respectively. Here, the asperity height distribution is regarded as a normal distribution, in which a standard deviation is \( \sigma \).

2.3 Load calculation block

Total load, \( P \), is obtained by summing the load on the asperity, \( P_1 \), and the load on the lubricant film, \( P_2 \), as follows.

\[
P_1 + P_2 = P \quad (3)
\]

In order to calculate the load, we must obtain the minimum lubricating film thickness, which influence each load \( (P_1 \text{ and } P_2) \).

The minimum lubricating film thickness, \( d_0 \), is calculated with consideration of EHL as follows [7].

\[
d_0 = 2.65a^{0.54}(\mu u)_{0.7}(E'')^{-0.03}B^{0.43} \quad (4)
\]

**Figure 3:** Load in boundary lubrication.

**Figure 4:** Model transformation for two surfaces contact.

**Figure 5:** Definition of equivalent radius.