A revolutionary technical development to revitalize Japanese forestry

— A proposal for a portable tree felling manipulator to address specific properties of Japanese forestry —

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First, we present issues in Japanese forestry based on an explanation of the specific properties of Japanese forestry. Then, taking the revitalization of Japanese forestry as a goal, we present a scenario for the achievement of that goal and comment on the type of research that is needed for it. This includes descriptions of the positioning and role of the technical development currently undertaken by the authors. As a concrete example of machine development, we report on the details of a manipulator for cutting down trees, "TATSUMI," and the results of verification tests. The TATSUMI manipulator is a machine that is compact and lightweight enough to be carried by a single worker. This machine cuts down trees using mountable/dismountable chainsaws that are commonly available at forestry sites. We also discuss new design methods for machine development that were identified as suitable for the mountain forests of Japan.

Keywords **:** Japanese forestry, design methods, manipulator, tree felling operation, mobility

1 Introduction

We are developing two types of manipulators that are capable of felling standing trees, and a transport mechanisms that can travel and carry heavy loads over uneven terrain of the mountain forests. We are also working on a system to measure and visualize forest information,[1] and a system to automatically create a road network for forestry operation in mountain forests, from various geographical conditions.[2]

In this paper, first, we explain the specific properties of the Japanese forestry. Then, we set the revitalization of Japanese forestry as the goal of research, present the scenario, and select the research topics that are necessary for achieving the goal. For the issues of safety and productivity of forestry, we have proposed and are developing some novel machines. In this paper, the "portable tree-felling manipulator TATSUMI" that is capable of cutting down trees in mountain forests will be discussed as our case study.

Each work environment and each target tree in mountain forests are unique, and the differences in environment and individual trees are great. The methods for felling trees rely heavily on experience, and there has been no numerical evidence. It is difficult to develop machines that work in the Japanese mountain forests, using the conventional design methods such as the V model or the agile model. Therefore, we sought a new design development method. This design method will also be explained in this paper.

2 Specific properties of Japanese forestry

The specific properties of Japanese forestry will be explained (Fig. 1). Compared to the United States or Europe, one reason that makes Japanese forestry difficult is the Japanese natural environment. Forestry is done in the "forests" in Europe, while forestry is done in the "mountains" in Japan. This is a fundamental difference. In the following sections, the uniqueness of Japanese forestry will be spelled out one by one to extract the research topics.

2.1 Type, quantity, and location of the forest resources

In Japan, forest covers 67 % of the land, and the absolute quantity of surface area (2.5 million ha) and growing stock volume (4.9 billion m^3) are high. What should be particularly

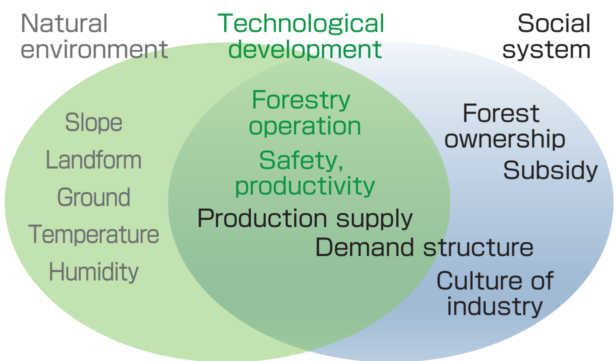

Fig. 1 Specific properties of Japanese forestry

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noted is that the growing stock per unit surface area is outstanding in Japan.[3] The growing stock volume moreover continues to increase. The increase is caused by artificial forests that were planted by humans. The amount a tree grows in one year is called the annual increment, and it is said that 70 % is allowable for harvest. About 70 % of the mean annual increment is harvested every year in Sweden, Finland, and Austria.[4][5] However, only about 20 % of the mean annual increment is harvested in Japan.[5][6] We should utilize the forest resources not only for forestry, but also for the preservation of the natural environment.

The above numbers are estimated values, and accurate understanding of where, what, and how much there is have not been obtained for this continuously growing forest resource. There are many cases where the owners and property boundaries are unknown which makes it even worse. These are also the points that complicate Japanese forestry.

The measurement of forest resources is mainly conducted for the purpose of grasping national resources and for the purpose of conducting forestry. It should also be pointed out that most of the measurements are done by hand.

2.2 Forest ownership

Europe and Japan take very contrasting stances on how the forest ownership is handled. The Japanese administration tends to work on protecting the ownership rights of personal property, while Europe has a system of calling owners to account along with the rights to ownership. Also, in the forest laws of Germany and Austria, the right to enter forests is given to all people.[7] In the survey done by the author in Germany, the burden on the owners that arises from other people entering privately-owned forests was estimated. One administrator replied that the owners sacrifice themselves for the sake of public good, therefore they are given subsidy money. On the other hand, the Japanese administration spends most of its time and money to find the owners to take care of the mountain forests.

2.3 Subsidy for forestry in Japan

The administrative investment, or subsidy, for building forestry roads and for forestation is 296.2 billion yen/year, and this surpasses the amount of lumber production of 214.3 billion yen/year (Fig. 2).[8][9] Of the forestry production amount, the production of mushrooms is 203.7 billion yen/year, and this is almost the same as the lumber production.[9]

In current Japanese forestry, many forestry businesses and unions engage in work as instructed by the administration to receive the subsidy money available at the moment, and the amount of subsidy is based on whatever the trend is at the time, and there are no definite rules. Innovation should originate from the sites. However, the current system does not provide an environment where people on site can engage in trial-and-error, originality or ingenuity.

2.4 Safety and productivity in forestry operation

2.4.1 Industrial accidents

In the 1970s, the accidents involving death and injuries in forestry surpassed 16,000 cases per year, and the number of deaths was nearly 250 people.[10] Comparing the occurrence of industrial accidents in forestry with other industries by "rate per 1,000 persons" that expresses the degree of occurrence of accidents, it is currently still the highest among all industries.

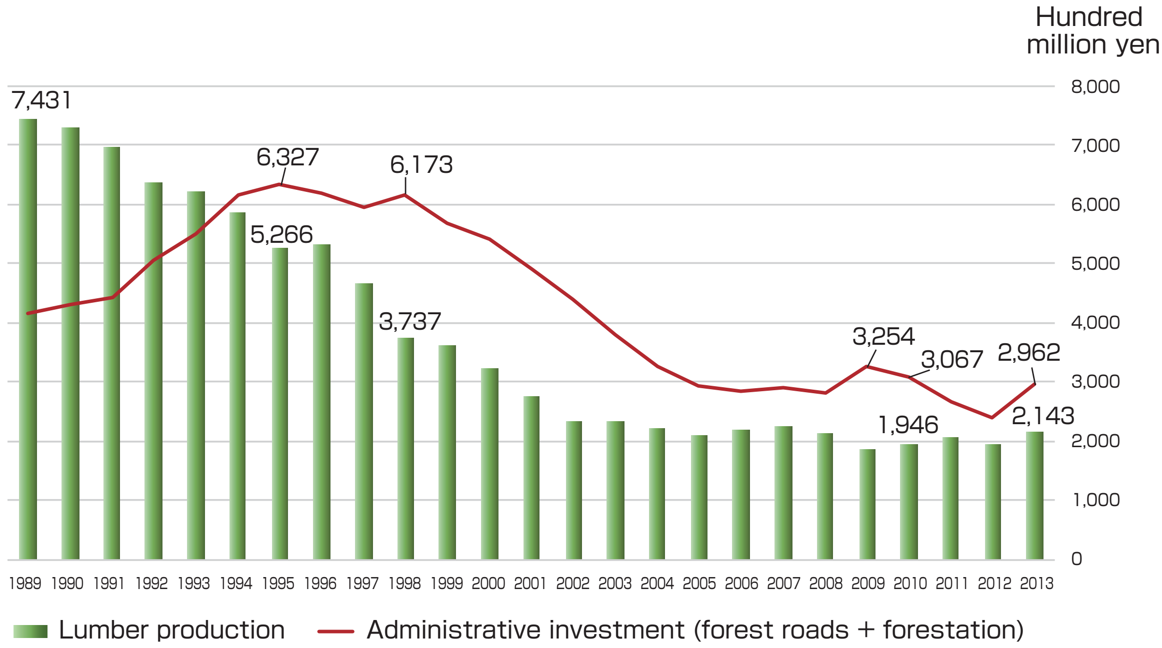

Fig. 2 Production amount of lumber and investment amount by administration[8][9]

While the average for all industries is 2.1, forestry stands out at 27.7 (2011).[11] Figure 3 shows the amount of industrial accidents in forestry. The serious accidents involving death and injuries were never less than 2,000 cases up to 2011, and most recently, there were 59 deaths in 2010.[10] Though the productivity of timber harvesting is low, before anything else, there is a major safety problem.

The tree-felling manipulator we are developing concentrates on the work of cutting trees. The tree-felling operation is the most dangerous operation in forestry, and the majority of industrial accidents occur during tree felling.

A worker holds a chainsaw with a blade that rotates at high speed (7,000–10,000 rpm), and stands right beneath the tree that he is cutting. The tree is 15 to 16 m high and weighs several hundred kg. Tree felling by humans has low accuracy and is unstable. Fatal accidents occur as the worker is struck by a high-speed rotating blade or is crushed by the tree that may fall in an unexpected direction.

2.4.2 Forestry machines

Along with the conventional forestry machines such as chainsaws, there are large heavy forestry machines.[Term 1] Moreover, there are two ways of collecting lumber: carrying the cut lumber on vehicles (the vehicle system) or hanging the trees on wire suspended in air (the wire system). Forestry machines of the vehicle system were developed in the US and Europe, and many are large heavy machines with multiple functions. In Japan, the attachments are imported from overseas, or even copied. And they adapt to the vehicle-type construction machines that are made in Japan. In some cases, the whole base is imported.

The large heavy forestry machines have increased from 23 machines in 1988 to 7,089 in 2014.[12] Subsidies are given to such machines, and the subsidy rate is one-half. However, even with this rapid increase, the production volume has not increased and the number of serious accidents have not decreased. Forestry in the US and Europe is conducted in rolling hill areas, and the large heavy forestry machines are made to work in such environments. It is difficult for such machines to fully show their capacity and performance in Japan.

Compared to the forests in the US and Europe, the Japanese mountain forests have steeper slopes, more complex landforms, and soft-ground terrains. Moreover, they have high temperature and high humidity, and the organization and maintenance/management of road networks are not easy as in the US and Europe. The road network density in mountain forests is low at 19.5 m/ha (2013).[13] Large heavy forestry machines that cut trees include the harvester and the fellerbuncher. These forestry machines cannot be driven on Japanese public roads, and must be transported on a trailer to the points where public roads meet forestry road networks. These forestry machines can enter the areas only where drivable roads are organized. Also, the work range is limited to the reach of the boom or arm.

Figure 4 shows the distribution of slopes in Shizuoka Prefecture. The percentage of forest coverage in Shizuoka is 64 %, and the forest covers the entire prefecture except for the urbanized area along the coast. The figure shows that the forestry is conducted in steep slope areas. It is dangerous to build roads on which large heavy forestry machines can be driven in the steep slope areas. To drive and to do forestry in

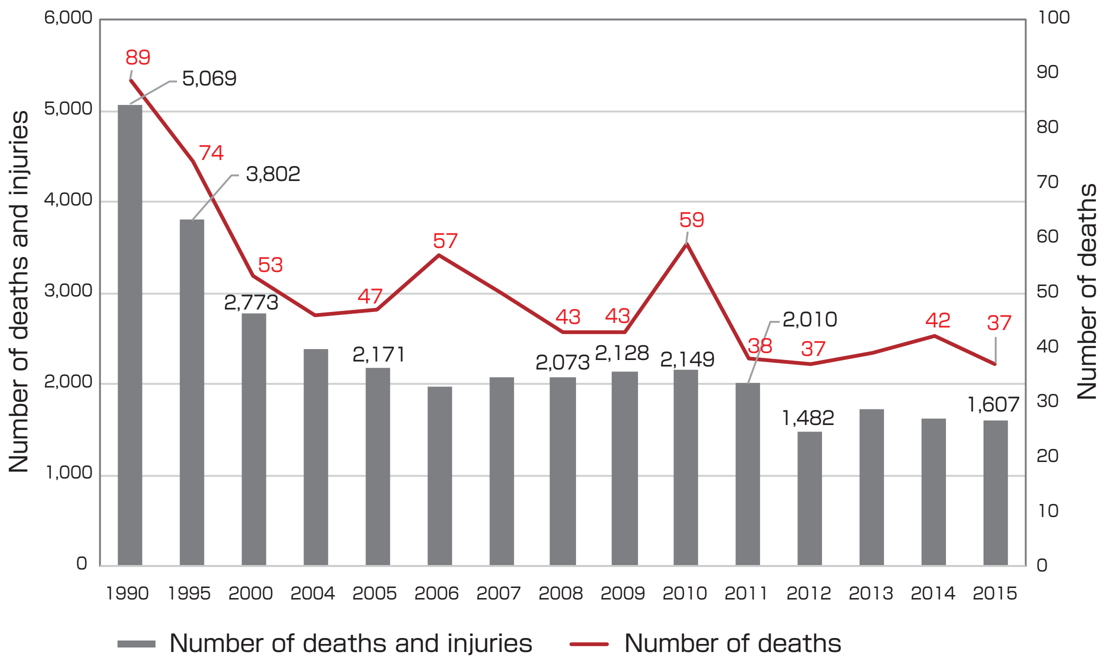

Fig. 3 Industrial accidents in forestry[10]

that area is even more dangerous.

Most of the tree-felling work in Japan is done by chainsaws even to this day. In a field survey by the author, a researcher of the University of Natural Resources and Life Sciences in Vienna answered that although the conditions are not as severe as Japanese mountain forests, Austria has relatively steep slopes within Europe, and 89 % of the felling work is done by chainsaws. In Japanese forestry, the "portable machines" that can be carried by humans such as chainsaws or a device proposed herein and the wire-type machines where the trees are hung on suspended wires continue to be used today, and improvement and development of such machines are necessary. Without these devices, timber cannot be harvested in many regions of Japan.

2.5 Production supply and demand structure

Another uniqueness of Japanese forestry is that the production and supply are done without a clear picture of outlets, quantity, or prices. If all the regions around Japan produce timber of similar quality at once only by inducement of subsidies, without knowing who will buy, how much, or at what price, the timber prices will decline. The price of Japanese timber continues to decrease and have become less expensive than imported timber.[14][15]

2.6 Culture of the industry

Chips and pulp are originally made from broad-leaved trees. Moreover, chips and pulp have low commercial prices, and the reproduction cost cannot be returned to the mountain forests if one produces only chips and pulp.

The Japanese cedar and Japanese cypress are planted to be harvested as construction materials. However, the domestic production volume has dropped, and the lumber material declined to 35 % (as of 2013) of the 1960s.[15] Even if one wishes to use solid natural wood that makes use of the property of wood itself rather than laminated wood or veneer, it is difficult to obtain such a material. The distribution is better for wood that is imported from abroad as lumber industrial products.

Particularly, the lumber needed for traditional Japanese wooden architecture is valuable, and the amount of wood used per unit surface area is high. However, traditional wooden architecture is difficult to build, even at a residential level, due to current laws as well as time and cost needed for construction permits.

Japan has had a culture of wood throughout its history, but the industry and culture that handle wood are declining. The industry and culture that raised the value of wood and contributed to the integrity of Japanese forestry are disappearing.

3 Objective and scenario

Many current artificial forests were planted during the forestation expansion period after the World War II, and they are ready for harvesting. The areas that were natural forests before forestation expansion have been planted and nurtured only by the instruction of the Government after the War. Therefore, people have very little experience in forestry. Yet, there are forests where forestry has been done since the medieval era in Japan.[16] Against the specific properties of Japanese forestry as mentioned before, importation or copying of the machines and extrinsic development using foreign systems will not endure. The revitalization

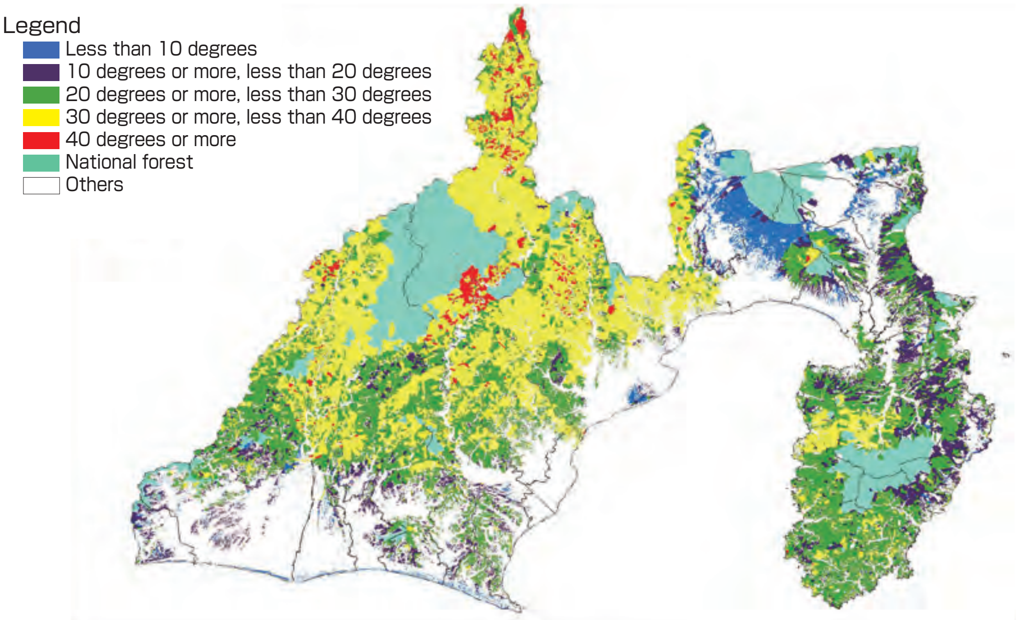

Fig. 4 Distribution of slopes in Shizuoka Prefecture (source: Shizuoka Prefectural Government)

of Japanese forestry must be based on Japanese nature, industrial culture, history, and local communities. Here, we set the revitalization of Japanese forestry as an industry as our goal, and we shall describe the elements and the scenario to achieve this goal.

As elements that must be studied for achieving the goal, other than technological issues, there are problems of inability to determine the owners or property boundaries of forests, difficulty of conducting efficient forestry due to strong rights of ownership, and the problem of the subsidy system, production supply, and demand structure.

First, innovation occurs on site. The ingenuity of the people on site, the ability to make decisions and carry responsibility, and the autonomy and sustainability of the industry must not be taken away. The damaging subsidy system, where the independence of private companies and on-site workers are destroyed, is contrary to the original objective. The subsidy money is not a tool to make people do what the administration wants, but it should be designed so the subsidized businesses and industries will take off and become independent of the administration.

One characteristic of forestry that should be pointed out is that the public function of forests contributes to the external effect that does not go through the market economy. In Europe, the maintenance of the public function of forests is perceived as “responsibility” that is attached to the “right of ownership by the owners. In Japan, it is the opposite, and there is a tendency to protect forests with public funds and systems because forests are considered having a public role even if they are privately owned.

Rather than designing a system where the person is compelled to do something using subsidies, which are our taxes, it is important for each person to play a steering role in a place where he/she is the main player. There is expectation for the administration to do things that can be done only by the administration, such as figuring out how to incorporate public and private roles of forests into the social system or how to create a system to recover and enhance the independence and sustainability of forestry as an industry.

Pertaining to the production supply and demand structure, it is necessary to revive distribution in our modern times by returning to the original purpose of tree planting, and by processing and high added value lumber that will bring back the reproduction cost to the mountains. This is the recovery of industry and culture that sees wood as wood. By reviewing the social mechanism that we have created, the technological development that aims at ensuring safety and productivity will become useful in severe natural environments. The vitalization of Japanese forestry will be limited with technological development alone.

3.1 Positioning and role of technological development of this research

Technological development should be inspired by the specific properties of Japanese forestry, rather than relying on foreign innovations. It is also necessary to “engage in technological development through ‘Japanese’ ideas when dealing with Japanese mountain forests.” Therefore, we propose technological development that is related to neither forestry machines from overseas nor conventional forestry machines, but somewhere in between.

Forestry operation begins from *jigoshirae*[Term 2] or preparation, goes through processes of planting, weeding, pruning, clearing and thinning, and then final harvesting. Harvesting starts with complete enumeration[Term 3] where standing trees are surveyed one by one, work of felling the trees, log-making where the branches are removed to form logs, yarding: collection where the timber is taken to the timber yard, and of transporting the timber to the market. Other than the trucks running on public roads, there must be some kind of technological development. According to the survey done by the author, it was found that technological development was necessary for felling trees in terms of safety, yarding for productivity, and weeding in terms of labor intensiveness.[17] In the scenario for technological development, the most important point is to decrease or eliminate the chances that people who work in forestry may die or get injured. The causes of industrial accidents must be removed from individual operations. Next, the productivity needs to be improved. To do this, it is necessary to develop an overall system to increase the efficiency of work by advancing each operation and linking the individual operations without any delay. It is necessary to build a production and distribution system that links the forests to consumers, from the timber yard in the mountains to the log market without any delay. It is also necessary to consider demand and supply, production, and mountain management in the future. Figure 5 shows the elements extracted for the goal and the scenario, and the positioning of our development.

3.2 Survey before starting the development of the machine

The author started a survey by visiting the tree-felling sites in mountain forests, forestry cooperatives, log and product markets, lumber mills, and others to collate needs with seeds. Then, application was submitted to the “New Interdisciplinary Field Research Strategy Access Survey” (FY 2006) of the Ministry of Agriculture, Forestry and Fisheries (MAFF), and the application was selected. In this project, the problems were organized, the technological demands were extracted, and the objective and topic settings were done. This information was presented in papers at the Robotics Society of Japan.[17][18] The findings up to this time of research from forests to timber to wooden architecture were reported to the general public in a book.[19] Afterward, on-site surveys in Japan and overseas were continued, the project was selected by MAFF in 2011, and the actual development of the machine started.

3.3 Approach taken to start development without precedence

As a technology for felling trees, there was an attempt at automation of chainsaws as a specialized vibration proof measure.[20] However, it did not reach practical use, and there was no more development after 1970. We were unable to start the development based on prior research. There were many given conditions that had to be considered in the design. Therefore, rather than starting by gathering representative values that would serve as design indices through simulation, we started by fabricating a simple machine and actually using it on site. Why did we start on site? That is because what can be expressed as numbers and words, and what can be determined based on them are limited. If a phenomenon is represented by a certain index, the phenomenon that is left outside the number is ignored. In machine development, it is necessary to nurture the experience and insight on site, very much like forestry technicians. Conversely, if the work does not require general perception or decision of a living human being, there wouldn't be so many industrial accidents, and a machine that can replace human workers would have been already developed.

3.4 Induce an optimal solution rather than one solution

The forestry worker looks at the diameter of the tree and determines the size of cut that will be made to the tree. This size is based on experience, and there is no numerical basis. In the work environment of mountain forests, no two conditions are the same including branches and leaves on the soil or forest floor, stumps, and position of the surrounding trees. Moreover, the differences are significant. Taking the example of water content in Japanese cedar, the individual differences among trees that are the target of felling work can range from 50 to 250 %. Even in one single tree, the direction of grain may differ depending on where the cut is made. Therefore, simulation that fits work environment and subjects into a single model may bring about one solution, but it is not known whether that solution is applicable to all other work environments or subjects. Therefore, we thought it was necessary to obtain an optimal solution rather than one solution. To do so, we created a prototype that realized the minimum movements, conducted actual operation on site, and went on to the next development from the results obtained. This process was repeated to approach the optimal solution model. As a result, we created a new design theory as presented below.

4 Creation of a new design theory

4.1 Design theory for a machine for Japanese mountain forest

Before starting the machine development, we found a new design development method, and by employing this method, we succeeded in demonstrating the effectiveness of the machine created in two years since the start of the development. It was a design theory that was inevitably reached after considering a machine that can be actually used on site, after surveying the sites of Japanese forestry.

There are design theories such as the V model[21] (Fig. 6). However, in developing machines for the Japanese mountain forests and assuming actual practical use, it was difficult to develop something that can be used on site, using the design method for machines that are generally imaged as robots. Machine that may be able to do everything may turn out to be useless in practice.

Taking the V model as an example, the process goes from the left-top of Fig. 6, then down, and reaches the right-top.[21] From the left-top to the bottom, all the requirements for design that

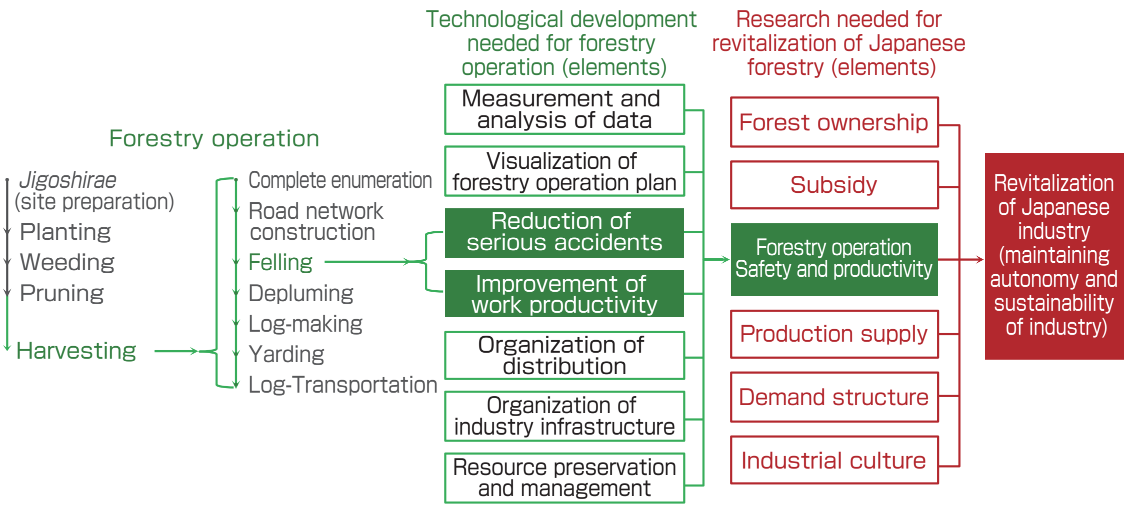

Fig. 5 Positioning of the technical development for the goal and scenario

one initially thinks of are thought out, the limiting conditions are considered, the specifications are carefully reviewed, and the design is narrowed down. A machine is developed, experiments are done from the bottom to the right-top, and the process finally reaches the demonstration experiment on site. In the design theory discussed in this paper, contrary to the flow, the process starts from the right-top, and a machine is operated on site to do the actual work. A machine with the minimum necessary moves is created, and is set to work at actual work sites. Rather than replacing all thinkable moves with machines, first, it is narrowed down to "this much must be done by machines" when working in the Japanese mountain forests. Those include heavy labor or maneuvers for which many serious accidents occur. In a natural environment, nothing is better than human sensing and control. It is not necessary to take these away from the workers as that may lead to danger. If all replaceable work is done by machine, the superiority of machines doing the work is lost. Cases of failure of surpassing the threshold are seen in robots that were developed for on site use. As a reaction, there is a tendency in robot development to realize robots with a single function only.

As the demonstration experiment on site of the right-top is started and the specifications become clear, the findings are incorporated into indoor experiments. It goes from the right-top to the bottom. The necessary functional requirements are added to the minimum motion needed for the machine, and the specifications are listed as a result. Finally, an overall system is created, and the flow goes from the bottom to the left-top.

The design theory of the development of our machine is summarized in Fig. 7. The objective of TATSUMI reported here is to ensure safety of tree-felling. To achieve this objective, first we aimed to have the most important "movements that must be done by a machine" with the ultimate simplification of the shape and mechanism of the hardware. There are no two same conditions for the environment and target for using the manipulator, and the differences are great. Therefore, if

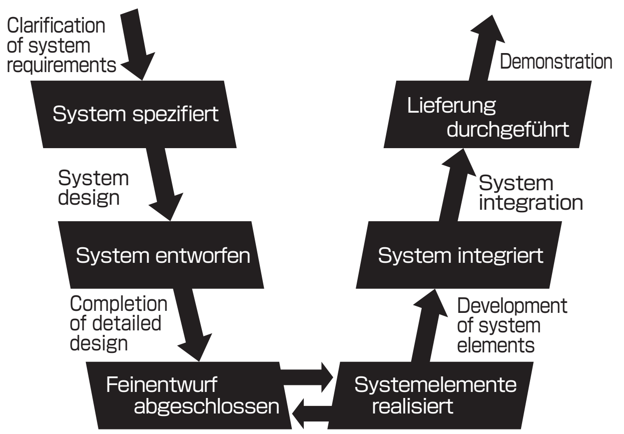

Fig. 6 V model[21]

specifications are clearly set at first and designed, the machine may become unusable in practice, and the specifications that have been once set may have to be changed. Therefore, it is necessary to rotate the "design spec determination loop" shown in red in Fig. 7. TATSUMI I and II were developed using this loop. This is similar to the design theory for the web, since it is similar to the characteristics of web technology where "one does not know who will use it, how he/she will use it, and in what kind of connection environment it will be used" and where "one does not know what will happen unless it is made, implemented, and run in the real world." In both cases, unless one experiences the operating environment including humans and the interaction, the specifications will not be usable in real society.

Next, we entered the development of TATSUMI III, and utilized the green "system integration loop." The development of this machine was the integration of the design spec determination loop and the system integration loop, and particularly, the development by the design spec determination loop was important.

4.2 Machine conceived from the sites of Japanese forestry

In the process of going from the right-top to the bottom in the design development process, we decided to use the commercial chainsaw in the tree-felling portable manipulator TATSUMI. If we had started from the clarification of system requirements in the left-top, we would have not used the chainsaw but started by designing the cutting function. Because we were creating a machine that could be used on site, we decided it was more realistic to mount/dismount an already available chainsaw.

A large heavy forestry machine harvester is also equipped with a saw chain. There is no better blade for cutting down

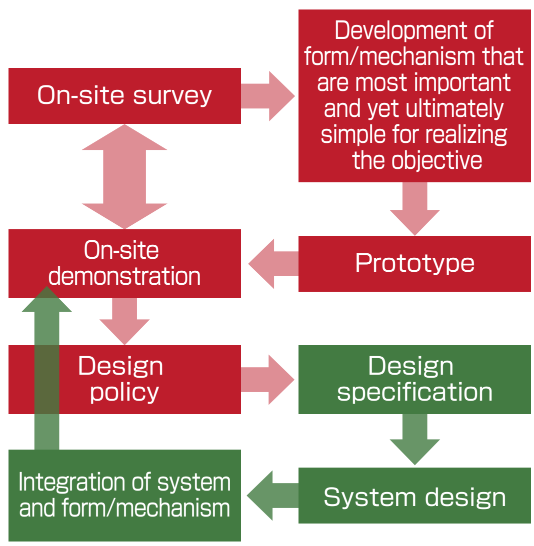

Fig. 7 Design spec determination loop and system integration loop

Table 1. Outline of developed machines

Name	Characteristic	Development period
TATSUMI I	Composed only of rectilinear pair,[Term 5] 3 degrees of freedom ※Feasibility of proposed machine investigated	2011-2012
TATSUMI II	Composed only of turning pair, 3 degrees of freedom	2012
TATSUMI III	1 rectilinear pair, 3 turning pairs, 4 degrees of freedom ※One manipulator model (optimal solution) presented	2012-2013
TATSUMI IV	1 rectilinear pair, 3 turning pairs, 4 degrees of freedom ※Joint improved, turn control function for chainsaw added	2013-2014
TATSUMI V	1 rectilinear pair, 3 turning pairs, 4 degrees of freedom ※Operability of installation, removal, setting and carrying improved by separating the fixture and working part of manipulator	2014-
TENRYU I	Composed only of rectilinear pair ※Feasibility of proposed machine investigated	2011-2012
TENRYU II	Develop and install drill/end mill with diameter of cut surface ※Main difference between II and III is blade length and cutting orbit.	2012
TENRYU III	Develop and install drill/end mill with half diameter of cut surface ※One manipulator model (optimal solution) presented	2012-
MOBILITY I	Composed only of crawler[Term 6]	2012-2013
MOBILITY IR	Composed of crawler and tow arm ※Hill climbing performance by tow arm improved	2013-2014
MOBILITY II	Composed only of newly developed crawler ※Response to load shift and position shift by unevenness of slope and ground improved	2014-

trees than saw chains. Chainsaws are widely used, as can be seen in the numbers: There are about 180,000 chainsaws being used (in 2014) according to official figures for about 50,000 forestry workers (numbers from 2010).[12] There is no forestry worker who does not own or use this tool. It is present at all sites. The road network density in forests is low at 19.5 m/ha (2013),[13] and most workers must reach the tree-felling site on foot. The Japanese chainsaws have evolved into a compact form. We aimed at downsizing and weight reduction of the manipulator by employing the chainsaw that is continuously being improved for small size and light weight.

Among accidents during tree-felling, a tree that a worker is cutting may fall in an unexpected direction and crush the worker. Also, a tree may fall in an unexpected direction and become a hanging tree,[Term 4] and this hanging tree may fall and crush the worker as the worker cuts the trees around the hanging tree. Deaths occur in such accidents. The worker concentrates on operating a chainsaw at the foot of a tree, and it is difficult to detect changes of movement of the nearby branches and changes in the situation. He may not notice when the tree starts to fall, and it may be too late to get out of the way leading to a serious accident. If the person is not holding and operating a chainsaw at the foot of the tree, such danger can be avoided. One of the reasons that trees fall in directions unexpected by the workers is because the accuracy cannot be obtained by human work. If chainsaws can be operated by machines, it will be possible to stabilize work accuracy, trees can be fell in the intended directions, and this can prevent workers being crushed by trees or hanging trees.

Moreover, the rotation of the chainsaw engine surpasses 10,000 rpm at full throttle. To maintain distance from this blade rotating at high speed during tree-felling not only will prevent serious accidents, but also will reduce vibration disorder.

By creating a distance between the worker and the trees and the chainsaw, industrial accidents that arise from these two danger factors are removed, and by stabilizing the cutting accuracy of trees through machine work, trees can be fell in intended directions. These were set as the objective of machine development.

5 Case studies

In this chapter, the results of the actual development will be described. Table 1 shows the outline of the developed machines. The machines include the manipulators to cut down trees named TATSUMI[22][23] and TENRYU[24] (Fig. 8), as well as the transport mechanism[25] (Fig. 9) that carries heavy items and follows the worker through forests where road networks are not available. In this paper, TATSUMI will be described. Details of the design and experiments on the tree-felling portable manipulator TATSUMI III and IV are given in the patent[23] and the paper[22] presented at the Japan Society of Mechanical Engineers.

5.1 TATSUMI I

TATSUMI I (Fig. 10) was composed only of a rectilinear pair[Term 5] that linearly moves the chainsaw in three axes. TATSUMI II (Fig. 11) that was developed next was composed only of a turning pair. In TATSUMI III (Fig. 19), the rectilinear pair and the turning pair were combined from the findings obtained from TATSUMI I and II.

The engine chainsaw was automatically operated by TASUMI I, and it was confirmed that the cutting operation could be accomplished normally. There were no looseness of chainsaw fixture or effect on the encoder by vibration, no leakage of fuel due to changes in machine positions that do not occur in normal use, no interruption of fuel supply, and it was possible to cut into trees in constant speed.

5.2 TATSUMI II

TATSUMI II was composed only of a turning pair, whereas TATSUMI I was composed only of a rectilinear pair. From the findings from I and II, the optimal type and arrangements of joints were investigated for TATSUMI III.

5.3 Design policy

The design policy obtained through the survey on site and TATSUMI I and II will be explained.

(1) The device must be the simplest possible mechanical apparatus resulting from the pursuit of ultimate simplification of the shape and mechanism of the hardware. Also requires minimal external recognition and control.

(2) Respond to diverse environment and diverse work with simple motion created by the machine. That is, the aim is a mechanical device that creates simple motion that can handle all patterns of work in all kinds of environment. The machine itself does not realize all patterns of work.

(3) For ideas of mechanism, *kata* (form) and *shosa* (gesture) that were handed down traditionally are valued.

(4) The aim is a mechanical device that can work with nimbleness and mechanism that utilizes the form and weight of the target, like in judo. Downsizing and weight reduction are achieved.

(5) The most important components in the work process are people.

In (1), a simplified mechanical device is aimed at by the pursuit of ultimate simplification of the shape and mechanism of

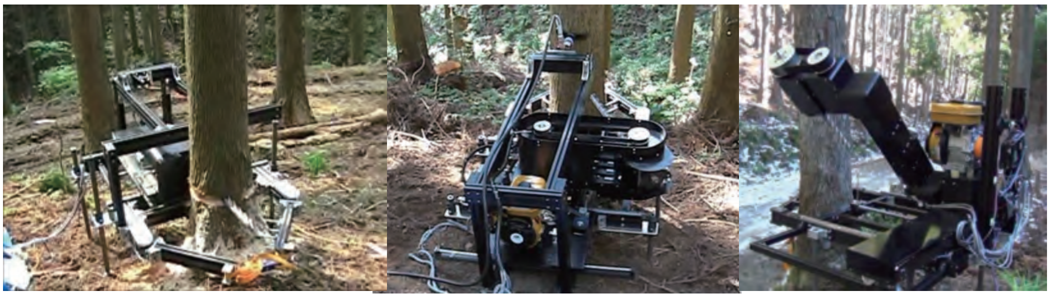

Fig. 8 TENRYU: From left I, II, and III

Fig. 9 MOBILITY: From left I, IR (improved I), and II

Fig. 10 TATSUMII: Composed only of rectilinear pair

Fig. 11 TATSUMI II: Composed only of turning pair

the hardware, and minimal external recognition and control methods are wanted. The reason is because the machines must endure the temperature differences, heavy rain, and heavy humidity in the Japanese mountain environment. The overseas forestry machines have corrosion problems of the electric circuits when used in Japan. The natural environment is composed of elements that are difficult to identify, and the control of a mechanical device by automatic sensing tends to cause malfunction, and that is dangerous in work involving a blade rotating at high speed. Also, daily maintenance and repair must be done by the on site workers. Therefore, the mechanical device must have a simple and easy to understand structure.

There is a machine with a similar concept as (2). This is the “yarder” that is a typical Japanese forestry machine. The yarder is a device that merely rolls out and rolls in wire. It can be used in any mountain forests. A chainsaw itself is also simply a rotating saw. However, it is possible to cut down almost any tree with a chainsaw. On the opposite side stands a complex machine called a humanoid robot. Various findings can be obtained in its development process. However, if a humanoid is to be used on site, it will be a different story. A machine that seems to be able to do everything like a human does makes the significance of people doing the work and the purpose for machines replacing humans ambiguous. Therefore the superiority of machines may be lost.

For the work itself, there are many operations that are perceived similarly in forestry. The most common tree-felling method is the *ukekuchi-oikuchi-giri* (undercutting and backcutting method).[Term 7] Basically, most trees can be fell by cutting three planes with a chainsaw. The TENRYU, which we are developing separately from TATSUMI, employs the *mitsuhimo-giri* (three-hinge tree felling method) that has 1,300 years of history in Japan.[26] The *mitsuhimo-giri* is the method for cutting down the sacred trees used to build the Ise Shrine. The tree is notched in three places, and almost any giant tree can be cut down safety. While the *yoki* (Japanese style axe) is used in the ceremony, TENRYU reenacts this operation by a manipulator equipped with a special blade that has functions of a drill and an end mill.[24]

In (3), the work method handed down traditionally is used in considering the mechanism. In the *ukekuchi-oikuchi-giri* (Fig. 12) employed in TATSUMI, the size of the *tsuru* (hingewood)[Term 7] (Fig. 13) is handed down based on experience and there is no scientific basis. However, in many cases, these traditional methods employ the most reasonable form and gesture as the technique has evolved over a long period of time.

In (4), the aim is to create a device that works with adeptness and mechanism that uses the form and weight of the target, or neutralizes the opponent like in judo, rather than taking on force by force like the large Western machines against tall, heavy targets (trees). In other words, the technological development is conducted using the Japanese concept.

In (5), people are the most important components in the work process, and the system we aim for is not totally automatic, but a system where workers can enter correction and support of the work as well as cognition and decisions. Therefore, the goal is a machine that can be used easily and intuitively by the workers.

5.4 TATSUMI III

5.4.1 Specifications

The specifications of TATSUMI III was derived from the results of TATSUMI I and II.

(1) Weight that can be carried by a single worker in mountain forests away from forestry roads: 18 kg or less
(2) Ensured self-sustaining operations: Uses an engine chainsaw (an electric chainsaw is not suitable for felling work in mountain forests)
(3) Workability: The chainsaw can be mounted and dismounted (the chainsaw is used also before and after the tree felling)
(4) Selection of a tree-felling method that optimally uses the chainsaw’s tree felling capability: Use of *ukekuchi-oikuchi-giri*
(5) Warrant the safety of workers during tree felling: Automatic operation (Trees, which are mostly cedar and cypress planted after WWII, are 15~16 m high and weighs several 100 kg. The work is done right beneath such trees, and the worker must handle a blade rotating at high speed. If the worker can keep a distance from these two elements, accidents can be prevented.)
(6) Target diameter and tree species: Up to 350 mm for thinning purposes; artificially planted cedar and cypress (*Cryptomeria japonica* and *Chamaecyparis obtusa*)

5.4.2 Cutting process

The sawing orbit by which a tree is cut is shown in Figs. 12 and 13. The *ukekuchi-oikuchi-giri* method described above is used. The tree-felling direction is to the left for both Figs. 12 and 13. The *ukekuchi* (undercut) is the triangular space that is made in the direction of tree fall, and the *oikuchi* (backcut) is a single planar cut made on the opposite side of the undercut. As it can be seen, the undercuttig and backcutting method is suitable for chainsaws that are good at making planar cuts, and just three planar cuts come to fell the tree. The part remaining between the undercut and the backcut is the *tsuru* (hingewood), and this is C in the figure. When the notch is made followed by the backcut, the hingewood acts as the hinge, and the tree falls in the direction of the undercut (to the left in Figs. 12 and 13).

5.4.3 Functional requirements

Based on the findings obtained from TATSUMI I and II, functional requirements were derived to approach the optimal solution.

(1) Lower the sawing plane: When the harvested timber is used as lumber, the area near the root where the maximum diameter can be obtained is the most valuable, and the height of the stump (sawing plane) should be lowered. (In III, the L-shaped arm was devised to eliminate the intermediate turning joint in II. As a result, the height of the sawing plane was lowered 150 mm in III compared to II.)

(2) The undercut is made by turning the chainsaw: As shown in the left side of Fig. 13, if the tree is cut by turning, the chainsaw does not have to be moved out of the tree, the movement range of the manipulator can be reduced, and the device can be reduced in size and weight.

(3) Backcut is made by moving the chainsaw parallel, rather than turning the chainsaw: If the backcut is made by turning like the undercut, the width of the remaining hingewood may become uneven, and there is danger that the tree fall may start unexpectedly while cutting. To avoid this, the backcut is made by maintaining the end line of the undercut (line where top and bottom notch cuts meet) and the direction of the guide bar is kept parallel.

(4) The arm itself is moved to widen the applicable diameter: If one tries to widen the diameter of the wood to which the device can be applied or the work area, under the condition that only the base of the arm turns and the movement of the arm itself is fixed, it is necessary to lengthen the arm. If this is done, the torque at the base joint increases, and the weight and size of the device increases. Therefore, by moving the arm parallel, the work area is widened while maintaining the small size and the light weight. III was designed with this method, and its maximum sawing diameter increased to 350 mm, and it could fell larger trees than II.

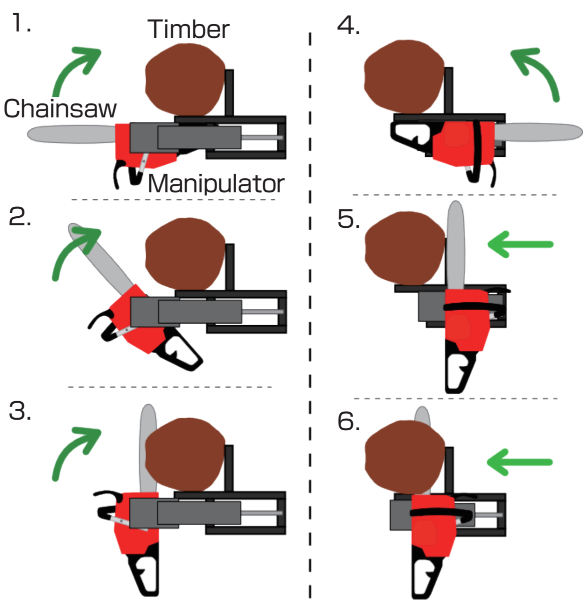

Fig. 12 *Ukekuchi-oikuchi-giri* method

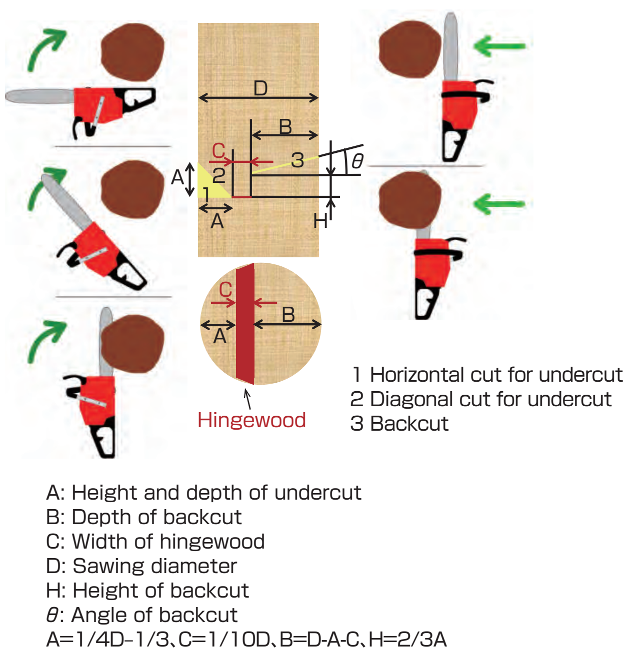

Fig. 13 Cut dimension and order of cuts

The undercut is cut by two turning moves, and the backcut is made with one horizontal movement.

5.4.4 Determination of major dimension—L-shaped arm

The overall form and dimensions (Fig. 14), the degree of freedom of arrangement (Fig. 15), and the rectilinear and turning allotment of each pair are shown. The first condition was to lower the height of the sawing plane. Therefore, an arm form where the height from the base, or the fixture position on the tree, to the chainsaw blade would be the lowest was considered. The mechanism that results in increasing the height was removed from between the base and the chainsaw. The chainsaw would not interfere with the arm when turning to undercut. The mechanism and form

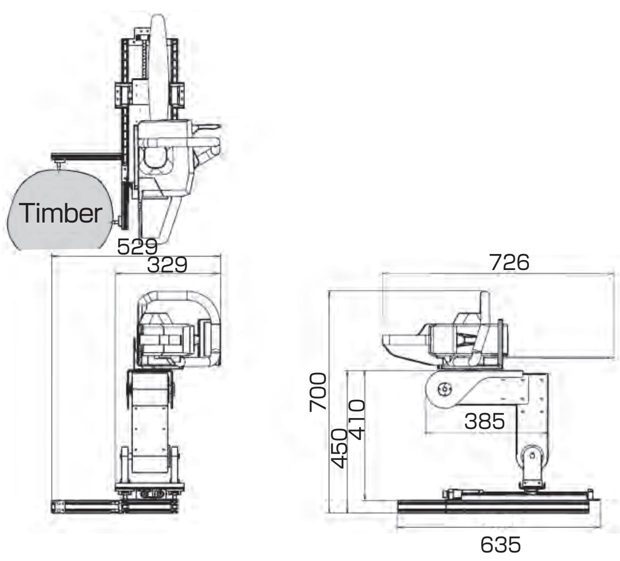

Fig. 14 Overall form and dimension

where the chainsaw came closest to the base were sought when the position for undercutting was taken. Based on these conditions, the design was done with the minimal dimensions that allowed holding the chainsaw, and we devised the L-shaped arm. The arm dimensions are shown in Figs. 16, 17, and 18. L1 and L2 are dimensions of the L-shaped arm, and L3 and L4 show the offset from the rotation axis at the tip to the sawing position when the chainsaw is mounted on the arm. The length of the linear motion part of the base was derived by calculating the amount of movement of the arm necessary for undercutting and backcutting.

The total weight of the manipulator is 18 kg or less, including the 6 kg for the chainsaw. The chainsaw used is ZENOAH (G3711EZ) with a 40 cc engine. The dimension in height is 700 mm, the longer direction size is about 725 mm, and shorter direction size is 529 mm, and it fits a space of 329 mm excluding the base bar.

5.4.5 Configuration of the joints

In this section, the number of joints and their arrangements are explained. To realize the aforementioned cutting process, a minimum of four degrees of freedom are desirable. Four joints are set: the lowermost joint for linear motion (Joint A, rectilinear pair), the joint to turn the chainsaw by the rotation of one axis (Joint D, turning pair), the joint to turn the L-shaped arm (Joint B, turning pair), and the joint to turn the chainsaw in the opposite direction (Joint C, turning pair). The range of motion of each joint is shown in Table 2.

The designs of each joint are explained. The chainsaw is made to cut forward due to the form of the saw chain. Therefore, the reaction force when cutting is at maximum when it first contacts with the tree and starts the cut. The reaction force was measured to be about 20 N. Other than using this value for the design of Joints A and D, the mechanisms of other joints were designed from the rotation moment in a stationary condition (Tables 3, 4, and 5).

Table 2. Range of motion of the joints

Joint	Range of motion
Joint A [mm]	0.0-320.0
Joint B [deg]	0.0-127.4
Joint C [deg]	-180.0-10.0
Joint D [deg]	32.0-45.0

In considering the mechanism, the method handed down traditionally is utilized. The undercutting and backcutting is done by workers using the chainsaw, and this is taught as one of the tree-felling methods with the least burden on the workers. This proposal substitutes the handwork with a manipulator, and it was confirmed that the manipulator would not be subject to excessive reaction force that surpasses human power in both TATSUMI I and II.

5.4.6 Control system

A program to numerically control the work was developed. With this algorism, the sawing orbit is automatically calculated from the timber size, and this is sent to the control program to control the manipulator. The machine language used is C++ considering its universality.

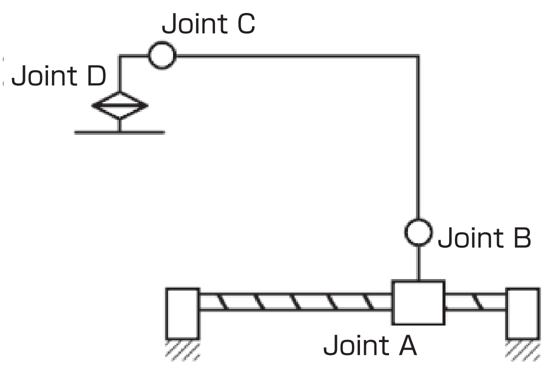

Fig. 15 Arrangement of degrees of freedom

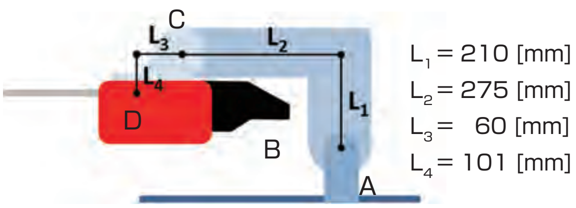

Fig. 16 Dimension of arm

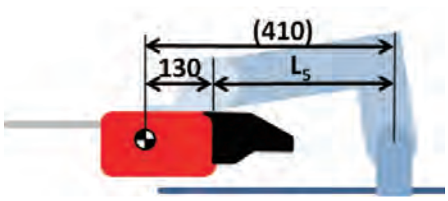

Fig. 17 Maximum extended size of Joint B

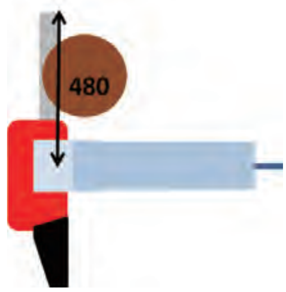

Fig. 18 Turn radius of chainsaw

Table 3. Reduction ratio

Joint	Name	Reduction ratio
Joint A	Gearhead	139:1
Joint B	Timing Pulley	3:1
	Hamonic Drive	160:1
	Total	480:1
Joint C	Timing Pulley	4:1
	Hamonic Drive	100:1
	Total	400:1
Joint D	Timing Pulley	4:1
	Hamonic Drive	100:1
	Total	400:1

Table 4. Specification of motor

	Joint A	Joint B	Joint C	Joint D
Maker	Maxon	Maxon	Maxon	Maxon
Model	RE25	EC60flat	RE30	RE30
Weight of motor [g]	130	470	260	260
Nominal voltage [V]	24	24	24	24
Assigned power rating [W]	20	100	60	60
Nominal torque (max. continuous torque) [mNm]	26.3	221	85.6	85.6
Max. speed [rpm]	14000	6000	12000	12000

Table 5. Specification of gear

	Joint A	Joint B	Joint C	Joint D
Maker	Maxon	Harmonic Drive Systems		
Model	GP26A	CSD-20-160-2UH	CSD-17-100-2UH	
Weight [g]	93	650	460	460
Reduction ratio	139:1	160:1	100:1	100:1
Permissible max. input rotational speed [rpm]	8000	6500	7300	7300
Permissible max. value of ave. load torque [Nm]	4.5	34	27	27

5.5 Verification Test

5.5.1 Demonstration experiment for TATSUMI III

A demonstration experiment to cut down trees in an actual mountain forest using TATSUMI III was conducted (Fig. 19). The location of the experiment was the Tenryu region of Hamamatsu City, Shizuoka Prefecture, and the subject was cedar of an artificial forest. The diameter at chest height was 240 mm, the sawing plane diameter was 265 mm, and the tree height was about 15 m.

The accuracy of the tree-felling operation is evaluated according to the size of the undercut and the backcut, the shape of the hingewood, and the direction to which the tree actually fell against the scheduled felling direction (actual tree-felling direction). The performance of manipulator III was evaluated according to this method.

It was verified that the operation from the horizontal cut of the undercut, the diagonal cut of the undercut, the removal of the undercut piece, the backcut after changing the position, and then the felling the tree could be accomplished with TATSUMI III.

One issue was that the diagonal cut for the undercut was lower than the targeted line, and the undercut became smaller. This was because the shaft that transferred the torque was not sufficiently stabilized in the joints at the base and the tip of the manipulator.

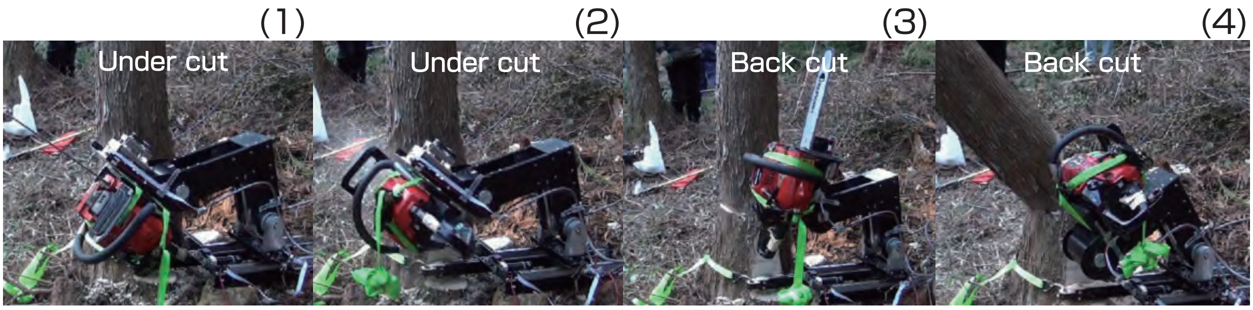

Fig. 19 TATSUMI III
(1) and (2) are diagonal cuts of the undercuts, (3) and (4) are backcuts.

5.5.2 Demonstration experiment for TATSUMI IV

In TATSUMI IV, the joint area of TATSUMI III was improved, the fixture base could be removed from the manipulator, and the rotation frequency of the chainsaw could be controlled remotely. In the four experiments conducted with TATSUMI IV (Fig. 20), it was verified that the operation from the horizontal cut of the undercut, the diagonal cut of the undercut, the removal of the undercut piece, the backcut after changing the position, and then the felling the tree could be accomplished. The sawing diameter of the four trees shown in Figs. 21 and 22 were D = 260 mm, 250 mm, 230 mm, and 270 mm, respectively. The times required from undercutting to felling were 278 s, 330 s, 219 s, and 267 s, respectively. The chainsaw made the cut into the tree at full throttle, and the manipulator moved the chainsaw at 5 mm/s.

5.5.3 Cutting line of the undercut, the backcut, and the hingewood

Fig. 20 TATSUMI IV

In forestry, the differences in skill of tree-felling are determined by the cutting line of the undercut, the backcut, and the hingewood. These were used for evaluation. The operation by humans is not stable, and the undercut and the backcut are not made accurately, and the hingewood does not turn out as intended. Therefore, in the work by humans, the tree may fall at unexpected timing in unexpected directions during the operation, and serious accidents may occur. The stability of work and sawing accuracy can be evaluated by the cutting line of the undercut, the backcut, and the hingewood that remain after the operation.

Figure 21 is a view of the cross-sections of the stumps of the fallen trees. Blue is the target line and red is the actual cutting line. In all experiments, the diagonal of the cutting line almost completely matched the target line. To control the felling direction of the trees, it is necessary that the undercut made on the tree side, to which it is expected to fall, is precisely cut out according to plan. In the experiment, the end line of the horizontal cut and the diagonal cut of the undercut matched. The operation by the proposed mechanical system was stable, and it was confirmed that the sawing accuracy was high.

Figure 22 shows the shape of the hingewood remaining on the stump. The target value of the program was that the hingewood width should be 1/10 of the tree diameter. Considering the phenomenon where the hingewood is torn when the log separates from the stump, the hingewood was made according to the program instructions. The guide bar of the chainsaw does not have constant width over its entire

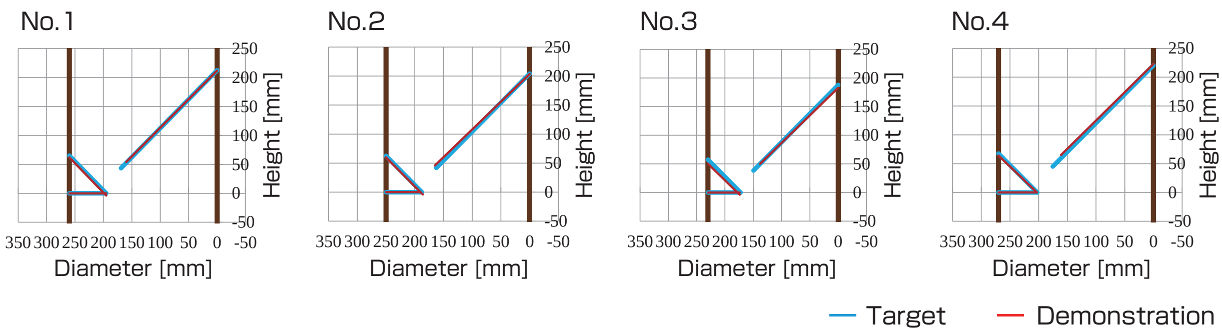

Fig. 21 Cut line of the undercut and backcut

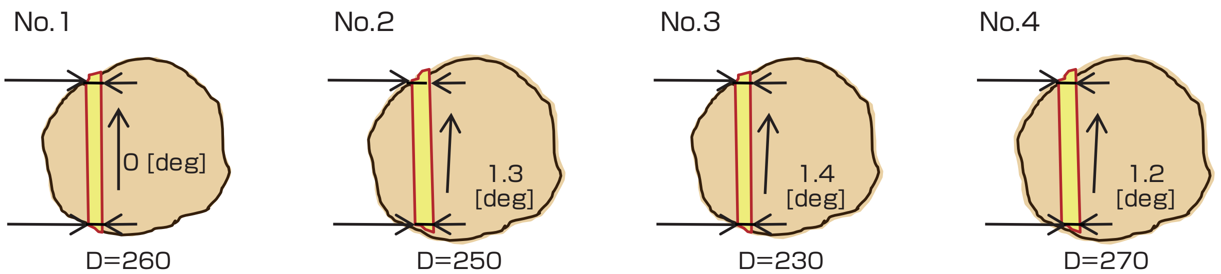

Fig. 22 Shape of hingewood

length, but becomes narrow at the tip like a rugby ball. It was predicted that when the sawing diameter approaches the effective length of the guide bar, the hingewood on the other side of the manipulator followed the shape of the guided bar and would be left thick. It was also predicted that the hingewood on the deeper side will be left thick due to the shape of the guide bar, it would be difficult to cut the hingewood, and the felling direction might be disturbed. However in the experiment, the hingewood width did not become uneven so as to affect the felling direction, and the error of felling direction was 1.4 deg or less, which was hardly significant.

Demonstration was done for the manipulator operation with the worker standing away from the tall, heavy tree and the chainsaw rotating at high speed that are often causes of serious accidents. The operation itself was stable, the sawing accuracy was evaluated, and we were able to demonstrate the effectiveness of the proposed manipulator.

5.6 TENRYU and MOBILITY

TENRYU realizes the *mitsuhimo-giri* using a special blade that has the functions of a drill and an end mill, rather than an axe. There were two and four blades in the end mill of the special blade for TENRYU I and II, and there were three in TENRYU III. The blade length that was the same as the sawing diameter in I and II was reduced to half in III. The tree-felling operation of trees was demonstrated with TENRYU III. Since then, improvements were made to increase the stiffness of the manipulator. For MOBILITY, after the development of I and the IR transport mechanism, II was developed after devising a new suspension mechanism based on the findings of the first two. The II transport mechanism demonstrated performance needed on uneven ground such as driving over the barrier of 245 mm only with a crawler[Term 6] on one side, assuming irregular ground in mountain forests.

6 Prospects for the revitalization of Japanese forestry

6.1 Prospect for TATSUMI

One of the roles of universities is to study the topics that are problems in society, think about how to solve the problems, and to propose new ways of thinking, mechanisms, and methods unseen before. We were able to present a certain optimal solution for maintaining safety in tree-felling operation through our research. In the future, we plan to hand over this new idea to a private company for realization and engage in development together. Since companies have different objectives than university research, development will take place with participation of corporate experts on sales and diffusion etc. Currently, the issues for TATSUMI are further downsizing and weight reduction, as well as improvement of ease of portability and installation on the tree. Another future prospect is the investigation of the chainsaw engine. The displacement of the engine chainsaw used in Japanese forestry is 40–60 cc, and for a person or a manipulator this is like having to hold up a motorcycle engine. Therefore, consideration is made for motors other than the engine and the separation of the blade and the power source.

The issue other than technology for TATSUMI is the diffusion method. From the manufacturing cost of the manipulator, we feel there is no particular problem for cost. The prices of large heavy forestry machines such as harvesters or fellerbunchers are tens of millions of yen just for the attachments.

6.2 Prospect for technological development

Of the elements that require research for the revitalization of Japanese forestry, the maintenance of safety and improvement of productivity in forestry are important for technological development. The order of technological development is first, to eliminate serious accidents from individual operations, next to improve productivity, and then, to construct the overall operation system that smoothly links one operation to the next. Even if the efficiency of one operation improves, if the operations before and after do not change, the operation stalls there. One harvesting operation may involve surveying the mountain forest, determining the target of harvest, cutting the trees down, gathering, and transporting, and the whole series of tasks must be improved to improve the overall productivity.

As described in Subchapter 2.1, the advancement in measurement of resource and data analysis for forestry is essential. The technological development is being started, but most of the tasks are currently still done by hand. Sophistication of this enormous amount of work is necessary. Also, how to set wires and road networks in mountain forests relies on experience and insight of the on site workers. Even if a landslide occurs, feedback cannot be done. At this moment, it is impossible to create a vision on how road networks are laid out in mountain forests and throughout the whole regions. The technology to visualize the management plan and how to carry on forestry from there are necessary. The technology to “make visible” the forest and the operation, or to be able to grasp the operations in real time, is desired.

6.3 Prospects other than technological development

In Chapter 2, the specific properties of Japanese forestry was explained, and it was pointed out that it was necessary to review the social system and establish a new plan, not only technological development. Here, the revitalization of Japanese forestry will be discussed from a different perspective.

In Germany, there are many people who engage in both farming and forestry, and there are some farming machines equipped with winches to pull the logs for forestry use. In Japan, there is almost no doubling with agriculture, and some people who work in other industries have even forgotten that they own mountains. With the appearance of machines like TATSUMI, I hope that people who do not specialize in forestry will become interested in the new Japanese forestry, and start taking care of our mountains.

Industrial products needs to be produced quickly and inexpensively, and the product value is highest when they are shipped and then tends to decline rapidly. Lumber, however, has the characteristic of gaining value over time through careful production, from growing the trees in the forests, processing including drying, and use in wooden architecture. It is necessary to regain a society that approves the production and distribution of such products and that appreciates the value. From the author's local surveys overseas, in Europe, the workers, the craftsmanship, and their work are valued in the community, and considerations are made for their coexistence in the industrialized society. Thinking of how to revitalize and to make independent industries such as forestry that concern mountain forests that cover 67 % of our land may give us a clue to revitalizing the local communities.

7 Conclusion

The TATSUMI project presented in this paper obtained development funds in 2011, the first machine was developed in FY 2012, and a manipulator model was proposed as III in the same year. III was able to conduct a series of maneuvers from undercutting to backcutting, and successfully cutting down trees while workers maintained a distance. In the following IV, the sawing accuracy was evaluated, and it was demonstrated that it could cut down trees in targeted felling directions. It was confirmed that there were no errors in the sawing accuracy and the operation was stable. Improvements are being made thereafter. The development aims for practical use from the beginning, and we believe our design theory is valid.

The author has engaged in research as a researcher and a consultant in a private company. There, research was required, and there were "partners" and "sites" with whom and at which problems had to be solved using the results of research. The partners and sites were never the same, the given conditions were diverse, and the clients' demands could not be fulfilled if one single value was used to fulfill a given condition. Therefore, rather than one solution, the optimal solution that resulted from the expert's experience and insight, or a mixture of senses and decisions, would be sought. What is important is to go to the site, experience, and understand, in order not to make mistakes in making decisions. In various fields, there is a sense of *déjà vu* at the destination reached. I think it is important in all fields to go to the site, to gain experience there, and to understand things.

Acknowledgements

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Terminologies

Term 1. Large heavy forestry machine[*1]: These include the harvesting and forestation machines with high work performance and multiple functions, as described in the Basic Policy for the Promotion of High-Performance Forestry Machine that was announced by the MAFF in 1991.

Term 2. *Jigoshirae*[*1]: Site preparation work conducted prior to planting the saplings, so the saplings will take root in the forestation area.

Term 3. Complete enumeration[*1]: Basic survey method to clarify the forest composition, including the measurement of tree stand growth.

Term 4. Hanging tree: The tree that is cut may become caught by the surrounding standing trees. Such hanging trees are unpredictable as to when they will fall, and accidents occur in the maneuver to dislodge the hanging trees.

Term 5. Pair[*2]: When two or more joints engage in limited motion under a mutual bond, the joints are in "pairs."

Term 6. Crawler: Caterpillar. A crawler has a belt with wider surface area that touches the ground compared to tires, and therefore has an advantage on weak or irregular ground. However, it is slower than tires.

Term 7. *Ukekuchi-oikuchi-giri* and *tsuru*:Undercutting and backcutting method is one of the methods of cutting down trees. In this method, first the *ukekuchi* (undercut) is made in the direction one wishes to fell the tree. The undercut consists of horizontal and diagonal cuts, and in Fig. 13, dimension A is 1/3 to 1/4 the diameter of the tree. Then, the *oikuchi* (backcut) is made from the opposite side, and dimension C of *tsuru* (hingewood) will be 1/10 of the diameter. The hingewood is the part that acts as a hinge when cutting down the tree. Normally, the backcut is placed horizontally. If the tree does not start to fall, a wedge is placed in the backcut and hit to make the tree fall. In this manipulator, the backcut is made diagonally rather than horizontally. This is to avoid interference of the hardware, and placing the cut diagonally will ensure that the tree will start falling on its own.

*1 Japan Forest Technology Association (ed.): *Shinrin Ringyo Hyakka Jiten* (Encyclopedia of Forest and Forestry), Maruzen (2001) (in Japanese).

*2 Robotics Society of Japan (ed.): *Robot Kogaku Handbook* (Robotics Handbook), Corona Publishing (1990) (in Japanese).

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Professor, Faculty of Science and Engineering, Waseda University. First class registered architect. Has authored *Shinrin No Hokai* (Collapse of Forest), Shincho Shinsho. Engages in research on the social infrastructure and its systems such as forest and water that are deeply intertwined with people's lives from a science and engineering perspective, and conducts technological development based on the findings. Wrote all parts of the paper.

Discussions with Reviewers

1 Overall

Comment (Naoto Kobayashi, Waseda University)

In this research, upon overviewing the current problems of Japanese forestry, an extremely ambitious and important goal is set, that is, to propose new technological development, as a way to solve the biggest problem that prevents forestry from becoming autonomous as an industry. The scenario to achieve the goal is built, and the specific method selected is to develop a tree-felling manipulator that is safe and easy to use. In this paper, the details of technological development are discussed, and at the same time, a new design method discovered in the process is introduced. The structure of the paper is clear and sound, and I believe this paper is suitable for publication in *Synthesiology.*

Comment (Yuki Imatomi, Tokyo University of Agriculture)

This is a commendable research paper on the R&D of new machines directed at ensuring safety that is a very important issue in forestry. In this paper, the goal is set as the revitalization of Japanese forestry as an industry, while considering the uniqueness of forestry in Japan, and the research elements for achieving the goals are presented. The research elements for achieving the goals and the positioning of the technological development elements can be understood well. Please consider reviewing the final draft so it can be easily understood by readers who are outside of this field.

2 Design theory

Comment (Naoto Kobayashi)

In this paper, the author states a unique design theory. Comparing it with the V model that was born in Germany, you state that your model starts from the right-top and goes to the right-bottom, that is totally different from the V model that starts from the left-top of V and ends at the right-top. The V model was born as a system design theory for software development, and it starts by clearly defining the requirements and specifications of the total system from the beginning. On the other hand, in a case where the environment in which the machine is used is extremely complex like the manipulator development in this research, the initial design spec may be unclear, and it must be changed along the way, even if it is defined at the beginning. Also, the author makes a comparison with the web design theory, and states that the theory of this paper is similar to that design theory. I think what is common is that the design spec of the system cannot be determined unless there are multiple interactions with the environment (including people). Even if the design spec is determined and a certain prototype development is assumed, further revisions will be necessary. Therefore, I think the process will be as follows for this design. First, there is a loop that determines the design spec, and one can determine the design spec by turning this loop around several times (TATSUMI I, II). Next, the system design and developments are done along a larger loop based on this decided design spec, and then the demonstration is done. I think this latter loop (TATSUMI III and others) is basically close to the V model. The design theory of this research is an integration of the "one design spec determination loop" and the "two system integration demonstration loop," and I understood that the former "design spec determination loop" is extremely important. Is my way of thinking in the right line?

Answer (Yuko Shirai)

I added a figure that shows the design spec determination loop and system integration loop in Subchapter 4.1, and also added a text explanation.

3 Need for using a portable tree-felling machine in the future

Comment (Yuki Imatomi)

Other than chainsaws, the forestry machines that can cut down trees currently include the fellerbuncher (that can cut down and gather timber) and the harvester (that has functions of cutting as well as log-making). In this research, you developed a tree-felling manipulator using the chainsaw. I think people's understanding will deepen if you clarify why people must continue using chainsaws or portable machines like your R&D machine in Japan in the future, by presenting data for the slope distribution in the forest area.

Answer (Yuko Shirai)

I added Section 2.4.2 "Forestry machines" and discussed the harvester and the fellerbuncher, and stated why it is necessary to continue using "portable machines" like the chainsaw or the R&D machines in Japan. Also, I presented the slope distribution map of Shizuoka Prefecture as an example.

4 Diffusion of the R&D machine

Comment (Yuki Imatomi)

In Japan, normally, the chainsaw is used for felling trees. Downsizing, weight reduction, and achievement of high performance have been done for the chainsaw as a portable machine, and this tool is essential in Japanese forestry. You are developing the tree-felling manipulator in this research from safety considerations, but I think the diffusion of a new machine is not easy because high-performance forestry equipment like the chainsaw already exists. I think you should mention the diffusion method for your machine as it nears completion.

Answer (Yuko Shirai)

I added the description about the prospects for diffusion in Subchapter 6.1 "Prospect for TATSUMI."