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A Pipe Route System Design Methodology for the Representation of Imaginal Thinking

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1. Introduction

Human beings have long been fascinated by figuring out the accurate answer to what the essential characteristic of human thinking really is. Besides, how knowledge is represented in human mind is also a mystery. However, limitations of development of traditional Artificial Intelligence framing of human thinking: logical thinking and intuitive thinking have deterred this process. Furthermore, such traditional AI framing has been challenged by Brooks' action-based AI theory with nontraditional symbolic representations and reasoning. Radically different from the above traditional views, we consider thinking in terms of images is the fundamental characteristics of human thinking and memory and knowledge are all stored as high dimensional images. Thereby we define this kind of thinking style as imaginal thinking.

Humans often think by forming images based on experience or knowledge and comparing them holistically and directly. Experimental psychologists have also shown that people actually use images, not descriptions as computers do, to understand and respond to some situations. This process is quite different from the logical, step-by-step accurate massive computation operations in a framed world that computers can perform. We argue that logical thinking and intuitive thinking are partial understanding to human thinking in AI research history which both explain part of, not all, the features of the human thinking. Though the applications of these descriptions helped the AI researchers to step forward to the essence of human thinking, the gap between the two totally different thinking styles still provokes vigorous discussions. We believe that the real human brain uses images as representation of experience and knowledge from the outer world to generate connection and overlap these two thinking styles. The images mentioned here are generalized, including not only the low level information directly apperceived by the sensing apparatus of human body, but also high level information of experiences and knowledge by imitating and learning. Imitation is the way human brain mainly learns experience and knowledge from the outer environment, which played an extraordinary role in helping human brain reach present intelligence through the millions of years of evolution. By imitating human imaginal thinking, a novel AI frame is founded trying to solve some complicated engineering problems, which is possible to take both advantages of human intelligence and machine calculation capability. Brooks' achievements in action-based AI theory also show indirect evidence of some basic ideas of human imaginal thinking, which is different in approach but equally satisfactory in result.

Just as the above mentioned, an effective AI frame has been constructed to solve some complicated engineering problems. Actually, when facing difficult engineering problems, lots of bio-inspired approaches, such as naturalistic biological synthesis approach and evolution inspired methodology have been tried and exhibited great advantage over traditional logical mathematic algorithms in improving system adaptability and robustness in uncertain or unpredictable situation. Take pipe-routing system for example, pipe-routing system design like aero-engine, not only a typical NP-hard problem in limited 3D space, must also extraordinarily depend on human experience. So as for pipe-routing, experienced human brain is often capable of providing more reasonable solutions within acceptable time than computer. So in the rest of this chapter, we'll focus on our current research: pipe route design based on imaginal thinking. A complete methodology will be given, and how computer simulates this process is to be discussed, which is mainly about the optimal path for each pipe. Furthermore, human's imaginal thinking is simulated with procedures of knowledge representation, pattern recognition, and logical deduction. The pipe assembly planning algorithm by imitating human imaginal thinking is then obtained, which effectively solved the problem of conceiving the shortest pipe route in 3D space with obstacles and constraints. Finally, the proposed pipe routing by imitating imaginal thinking is applied in an aero-engine pipe system design problem to testify the effectiveness and efficiency of the algorithm.

The main idea of this chapter is by intercrossing investigations of the up-to-date research accomplishments in biology, psychology, artificial intelligence and robotics, trying to present the truth of human thinking so as to understand the fundamental processing style of human brain and neural network and explain the problems which has been confusing the artificial intelligence research, such as what the human thinking is, how human thinks, how human learns and how knowledge is represented and stored. Our work may bring us closer to the real picture of human thinking, then a novel design methodology of pipe-routing system integrating the human imaginal thinking and logic machine computation capability is presented. The holistic layout of pipes is represented as images of feasible workspace, which reflect human experience and knowledge; the optimal path for each pipe is quickly decided by applying the translational configuration space obstacle and the improved visibility graph imitating human pipe-routing behavior. The simulation demonstrated the effectiveness and high efficiency of our pipe-routing design method.

2. Imaginal thinking: It's origin and style

In this part, we will discuss what human thinking is, from step-by-step analysis, the mystery of human thinking style will be revealed and people will find imaginal thinking exist in the whole thinking process. First, human thinking does not exist without intermedium, instead the real biological organs are the hardware which human thinking relies on. Therefore, we will introduce the biological foundation for human thinking: neurons and neural network. After that, we will generally define the human thinking process, and definition here is descriptive. As a biological process the human thinking is, we will discuss what really happens during the thinking in detail. At last, we will classify the human thinking styles with reference of past research in artificial intelligence. Among all the thinking styles, the most fundamental also the most important style is called imaginal thinking, as it covers all the other thinking styles which makes other thinking style a special appearance of imaginal thinking.

2.1 What is human thinking?

2.1.1 The biological basis of human thinking

A neuron (also called a neurone or nerve cell) which is an electrically excitable cell can process and transmit information by electrical and chemical signaling. The synapses, specialized connections with other cells make chemical signaling possible. These connections by neurons to each other can further form networks. Neurons are fundamental elements of the nervous system, which includes the brain, spinal cord, and peripheral ganglia. We can classify neurons according to their specific functions like sensory neurons, motor neurons, and interneurons. A typical neuron is made up of a cell body (often known as the soma), dendrites, and an axon. Dendrites are filaments generating from the cell body which often stretch for hundreds of microns and branches multiple times, resulted in a complicated "dendritic tree". An axon, known as a special cellular filament, arises from the cell body at a site called the axon hillock and extends for a distance, as far as 1 m in humans or even more in other species. Multiple dendrites can be frequently brought about by the cell body of a neuron, although the axon may branch hundreds of times before ending but never more than one axon can be generated. As for most synapses, signals are usually transmitted from the axon of one neuron to a dendrite of another. However, as we know, nature is fed up with specialties, the same applies to neurons which means many neurons violate these rules: neurons lacking dendrites, neurons having no axon, synapses connecting an axon to another axon or a dendrite to another dendrite, etc are all examples of this kind of exception.

All neurons are electrically excitable which denotes that they can maintain voltage gradients across their membranes. This mechanism is realized by metabolically driven ion pumps, which manipulate ion channels embedded in the membrane to generate intracellular-versus-extracellular concentration differences of ions such as sodium, potassium, chloride, and calcium. The function of voltage dependent ion channels can be altered by changes in the cross-membrane voltage. An all-or-none electrochemical pulse called an action potential is generated when the voltage changes large enough. This pulse traveling rapidly along the cell's axon activates synaptic connections with other cells when arriving.

As we can see, the neurons and the networks they form are fundamental hardware for human thinking. Although lots of mysteries haven't been solved, we believe multiple networks and various patterns of connection are relevant to people's thinking style which is denoted as imaginal thinking in this article. To some extent, we propose people's thoughts and memories are actually projections of these numerous structures of networks.

2.1.2 Definition of human thinking

First, it is important to clarify that human thinking are forms and images created in the mind, rather than the forms perceived through the five senses. Thought and thinking are the processes by which these imaginary sense perceptions arise and are manipulated. Thinking allows beings to model the world and to represent it according to their objectives, plans, ends and desires. Similar concepts and processes include cognition, sentience, consciousness, ideas, and imagination.

The general definition of human thinking: representative reactions towards stimuli from internal chemical reactions or external environmental factors. This definition precludes the notion that anything inorganic could ever be made to "think": An idea contested by such

computer scientists as Alan Turing. Different research domains have different research methods and focuses on human thinking.

Philosophy of mind is a branch of modern analytic philosophy that studies the nature of the mind, mental events, mental functions, mental properties, consciousness and their relationship to the physical body, particularly the brain. The mind-body problem, i.e. the relationship of the mind to the body, is commonly seen as the central issue in philosophy of mind, although there are other issues concerning the nature of the mind that do not involve its relation to the physical body^[1].

Our perceptual experiences depend on stimuli which arrive at our various sensory organs from the external world and these stimuli cause changes in our mental states, ultimately causing us to feel a sensation, which may be pleasant or unpleasant. Someone's desire for something to eat, for example, will tend to cause that person to move his or her body in a specific manner and in a specific direction to obtain what he or she wants. The question, then, is how it can be possible for conscious experiences to arise out of a lump of gray matter endowed with nothing but electrochemical properties. A related problem is to explain how someone's propositional attitudes (e.g. beliefs and desires) can cause that individual's neurons to fire and his muscles to contract in exactly the correct manner.

Psychologists have concentrated on thinking as an intellectual exertion aimed at finding an answer to a question or the solution of a practical problem. Cognitive psychology is a branch of psychology that investigates internal mental processes such as problem solving, memory, and language. The school of thought arising from this approach is known as cognitivism which is interested in how people mentally represent information processing. It had its foundations in the Gestalt psychology of Max Wertheimer, Wolfgang Köhler, and Kurt Koffka^[2], and in the work of Jean Piaget, who provided a theory of stages/phases that describe children's cognitive development. Cognitive psychologists use psychophysical and experimental approaches to understand, diagnose, and solve problems, concerning themselves with the mental processes which mediate between stimulus and response. They study various aspects of thinking, including the psychology of reasoning, and how people make decisions and choices, solve problems, as well as engage in creative discoveries and imaginative thoughts. Cognitive theory contends that solutions to problems take the form of algorithms - rules that are not necessarily understood but promise a solution, or heuristics - rules that are understood but that do not always guarantee solutions. Cognitive science differs from cognitive psychology in that algorithms that are intended to simulate human behavior are implemented or implementable on a computer.

In conclusion, we know that thinking is a mental process, by which living creatures connect themselves to the outer world and form cognition styles. Thinking can also be considered as the information processing when forming concepts, making solutions, deduction and decisions. Thinking is possibly an idea, an image, a sound or even a desire aroused in mind.

2.1.3 Human thinking

In artificial intelligence history, people use their own methods to study on human mental activity and intelligence. Therefore, there are many different assumptions to artificial intelligence, such as symbolism, connectionism, and behaviorism^[3]. Symbolism and connectionism have a long history with more supporters, meanwhile, arguments and

divergences lie between the two main widely accepted research domains of artificial intelligence. Different from traditional artificial intelligence, behaviorism takes a new path, which is supported by convincing experimental results.

Here we introduce some of the basic assumptions and ideas of symbolism, connectionism, and behaviorism, and then we propose our assumption on human thinking.

2.1.3.1 Symbolism

Symbolism has the longest history in AI, also the widest application and influence. The name of 'artificial intelligence' was firstly proposed by symbolism believers. The symbolism still takes the leading position in AI, and the successful applications include problem solving, computer gambling, theorem proving, and expert systems which bring historical breakthrough to symbolism applications. Symbolism, also called as symbol method or logicism, is the AI theory based on symbol processing which was first proposed by Newell and Simon in their 'Physical Symbol System Hypothesis'. The hypothesis considers all the intelligent creatures as a symbolic systems, the intelligence comes from symbol processing. By using symbols to represent knowledge and deduction based on symbols, intelligence may be fulfilled.

There are some challenges to symbolism. First, human does not rely merely on logical thinking to solve problems; no-logical deduction also plays an important role in human mental activities. For example, the visionary senses are mainly based on images which can hardly be represented as symbols. Second, when the knowledge database reaches such a huge volume that how to manage and search in the database in acceptable time is a main technical problem, known as 'frame problem', which some affirm never to be solved. Finally, even the frame problem was solved, the intelligent system realized by symbolism still could not own human intelligence. After all, searching the database is not the way human deals with problems.

2.1.3.2 Connectionism

Connectionism is also called connection method or neural calculation, which imitates human neuron structure as the main method to realize intelligence. The major tool being used is called artificial neural networks, which is also formed by connections between large volumes of neurons.

Connectionism uses a concept opposite to symbolism, which focuses on the structure of the intelligent machine. Connectionism, a bottom up concept, believes only if the machine has the same structure as human brain, it will own the possibility to have intelligence. Symbolism, a top down concept, considers that the high level intelligence has nothing to do with the low level mechanism; as long as the intelligence is obtained, it does not matter to use what kind of structure.

A prototype of artificial neural network is a piece of empty paper which has no intelligence. Learning and training are essential in adjusting the network structure and weights of connections between the neurons, so as to obtain the knowledge to solve the problems. Therefore, in connectionism, the learning problem is more crucial than the structure problem. To solve the problem, study on machine learning is unavoidable.

2.1.3.3 Behaviorism

Behaviorism, also called behavioral intelligence or behavioral method or cyberneticism, is the intersection between cybernetics and AI. Behaviorism is based on 'perception-action' model, which considers the intelligence is from perception to action, also from the adaptation to the complex outer environment, rather than representation or deduction. Thereby, the fundamental units of intelligence are simple behavior, such as obstacle avoiding and moving forward. More complicated behavior generates in interaction with the simple actions. Another point of view of connectionism is: since it is difficult to realize human level intelligence, why not lower the requirements, just make low level intelligence similar as insects. Then, with biological evolution, maybe we can realize the required artificial intelligence.

With these ideas, the most influential scientist of connectionism, Rodney A Brooks, made a six-leg insect-like robot with 150 sensors and 23 actuators. The mechanical insect robot has no deduction or planning capability as humans, but it showed much better performance in handling the complex environment than former robots. It has agile bumping prevention and cruising capability in non-structural or framed world. In 1991, Brooks published the paper 'intelligence without representation' and 'Intelligence without reason', challenging the traditional AI beliefs and opened a door to a new research direction in AI.

Brooks' revolutionary work has roused both support and challenge in behaviorism. Some consider the success in robot insect cannot guarantee high level intelligence, and the evolution from the insect to human is just an illusion. Despite all, the behaviorism is still a feasible and necessary method to realize AI.

2.1.4 Human thinking: Our attempted hypothesis

From the above discussion we can see, the traditional AI theory in understanding human thinking is limited. Such traditional AI frame [4-5] provoked vigorous discussion, and has especially been challenged by Brooks' action-based AI theory which uses a direct and tight connection from perception to action with nontraditional symbolic representation and reasoning [5-6]. Experimental psychologists have also shown that people actually use images, not descriptions as computers do, to understand and respond to some situations [7]. Hereby, we propose our hypothesis on human thinking, as shown in Figure 2.5.

First, human thinking must be a stimuli-responding process from perception to action. The stimuli can be external, such as sight, touch, taste, smell, and sound; or internal, such as hunger, pain. Both the external and internal stimuli are sensed by neural excitations (although some of the correspondences between the neural excitation and internal stimuli are still not clear, the existence of such correspondence is pretty sure); such process is defined as perception. The stimulated sensory neurons generate neural signals and propagate in neural networks through synapses of interneurons in a certain style which forms the action potential in motor neurons so as to cause muscle contraction (although how neuron excitation accurately controls muscle contraction is still not clear, we know that certain action somehow corresponds to the stimulation by external observation); such process is defined as action. Such perception to action process is similar as Brooks' ideas and definition in behaviorism. Human thinking happens during the process of perception to action.

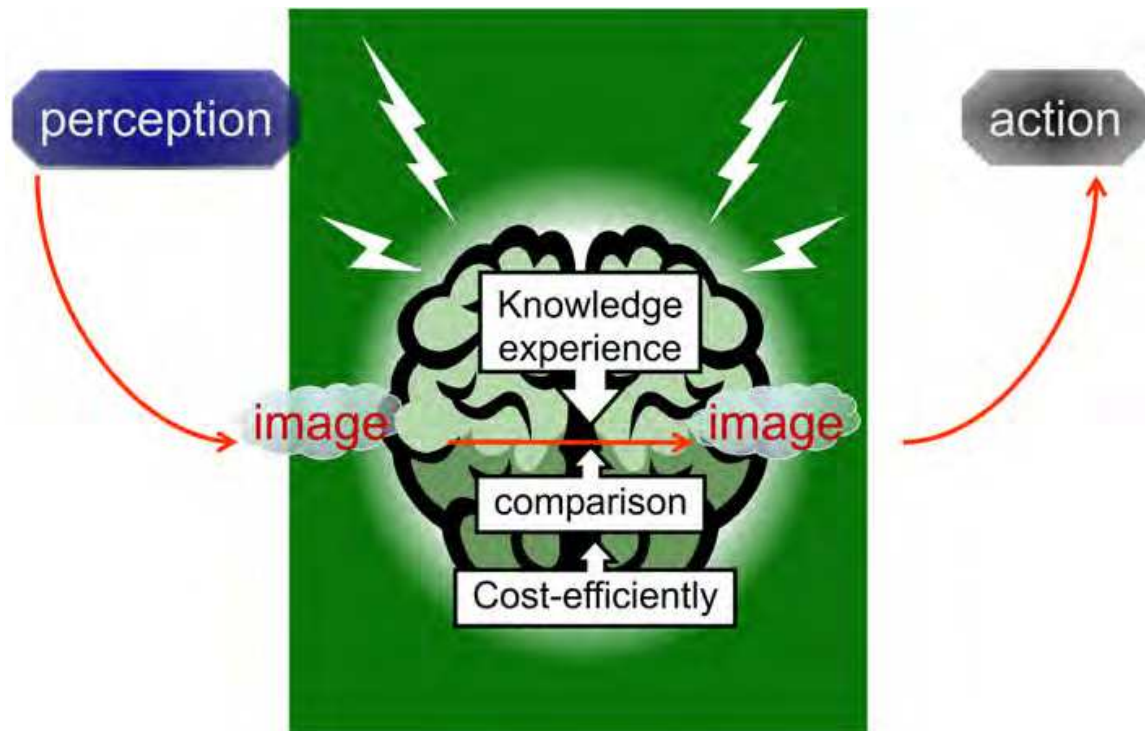


Fig. 2.5. Human thinking processes

Second, the information in thinking process is high dimensional images. Of course, the information discussed here is not referred to single neuron signaling. As known to all, a single neuron signal is caused by changing voltage difference between inner and outer sides of membrane by opening the ion channel. The information discussed here represents signals in the huge neural network formed by synapses when humans respond to a certain perception. Every single neuron signal is one dimensional. With average 10^{11} neurons and 7000 synapses of each neuron, the one dimensional signals may present high dimensional information by coordination among all kinds of neurons (some neurons transmit the signal one way, others transmit multi-ways). Such high dimensional information is defined as images. However it's important to clear that the information is not limited to real images, this definition applies to all the information that can be understood in human mind as forms of images. Any signal form like sound, perception and emotion can all be images, as long as the high dimensional information stimulates various neuron architecture models formed by certain synapses and neurons in neuron networks (or a neural excitation graphics) to express different modes of information.

Third, the high dimensional neural network, namely the activated synapses and corresponding neurons by responding to certain high dimensional signals, can be formed in two major ways. One is by in heritage of biological evolution. Some vital knowledge of surviving in the out world has been recorded in human DNA, so some of the synapses are formed in fetus phase, such as spinal reflection mechanism, crying, breathing and milking. The other way is the interaction with the out environment based on one single purpose – survival. Such animal instinct leads to a more fundamental biological behavior, which is consuming less energy to accomplish more activities. Such process trains human neural network and forms synapses. The network is formed when human finally reaches mature phase which can be proved by the changing numbers of human neural synapses indirectly.

Human neural synapses increase as growing up, which means the inherited neural network may not be sufficient in surviving the environment so new synapses continue to grow. At 3 years old, human synapses' number reaches the peak of 10^{15} . This number decrease ever since, meanwhile human interacts with the environment and forms corresponding network excitation to stimuli, such network must use lowest energy and therefore high energy consumption synapses disappear. Based on evolution and survival instinct, human gets training and learning in the environment and forms the responding neural network structure, such process is the way human forms intelligence.

At last, human thinking is the process by comparing the past knowledge and experiences, also the process from lowest energy consumptive neural network to highest ones. During the interaction between human and environment, knowledge and experience are absorbed corresponding to specific stimulations respectively, which are presented and memorized as groups of synapses and their neural networks. The knowledge and experience can be obtained as high dimensional images which map to different neural network structures and solutions to different kinds of problems and tasks with different levels of energy consumptions. Humans always try to solve any problem by using low energy consumptive solutions; only if the feedback shows an uncompleted task, the higher energy consumptive solutions will be taken into consideration. When all the stored experience and knowledge cannot fulfill the requirements of problem solving, human will feel incapable and tired of thinking since metabolism in neural system has reached an unusually high level. One thing noticeable is that the handling of using what kind of energy consumptive level of neural networks is also represented as neural networks, which use same forms and functions of structure in memory, information management, calculation, perception, signaling, generating motion potential, and motion control, which is totally different from the infrastructure of computers.

To sum up, we may conclude human thinking as a process of generating responses to the stimuli starting from perception, by trying different solutions with the sequence of from low energy to high energy through signaling in neural networks, thus finally generating motion potentials meeting specific responsive needs and controlling the motor neurons to actuate or restrain the actions through motion neurons from specific neuron networks.

2.2 Imaginal thinking style

2.2.1 Definition to imaginal thinking

Human thinking is one kind of animal instincts for survival, which is acquired through inheritance or learning, to respond to the outer or inner stimuli. The different energy consumptive neural networks corresponding to different knowledge and experience. The motion potential is formed by searching and comparing the neural networks from low energy to high energy so as to actuate or restrain the motions to fulfill biological demands.

Since the information and signals processed during thinking are represented as high dimensional neural images which are appreciable and imaginable, so we define such thinking style as imaginal thinking. The confusion needs to be clarified with traditional thinking style in form of images. The images in imaginal thinking are generalized, which not only include the low level perceptive information, but also cover the high level experiential information. The word image in imaginal thinking is a metaphor, similar as the definition of

hyper-dimensional concepts. Human intelligence is formed by millions of years of evolution, which makes it impossible for anything non-biological to have such thinking style, unless it has biological neural network functions or characteristics.

2.2.2 What happens in imaginal thinking?

The ultimate purpose of imaginal thinking is forming motion potentials, so as to actuate or restrain the motor neurons. Such thinking procedures can be further divided into two categories as learning and non-learning. The non-learning procedure can also be considered as problem solving procedure.

2.2.2.1 Learning procedure

Learning procedure, as shown in Figure 2.6, happens when the former experience and knowledge are insufficient to satisfy the responding demands. Human has two major ways of learning which are imitation and observation. Both the experiments on capuchin monkeys [8-9] and the study on the social learning show solid evidences for the importance of imitation in learning[10-11]. The existence of mirror neurons shows that when human imitates or observes a certain action, mirror neurons in human brain will excite unexceptionally. By using the modern scanning and imaging technology, the distinct functional areas are found in cortex mapping the respondents to different stimuli which includes the five senses. The learning experiment on mice shows that the repeating stimuli will cause growing new dendrites, connections and synapses, so as to form new neural network to represent new knowledge and experience.

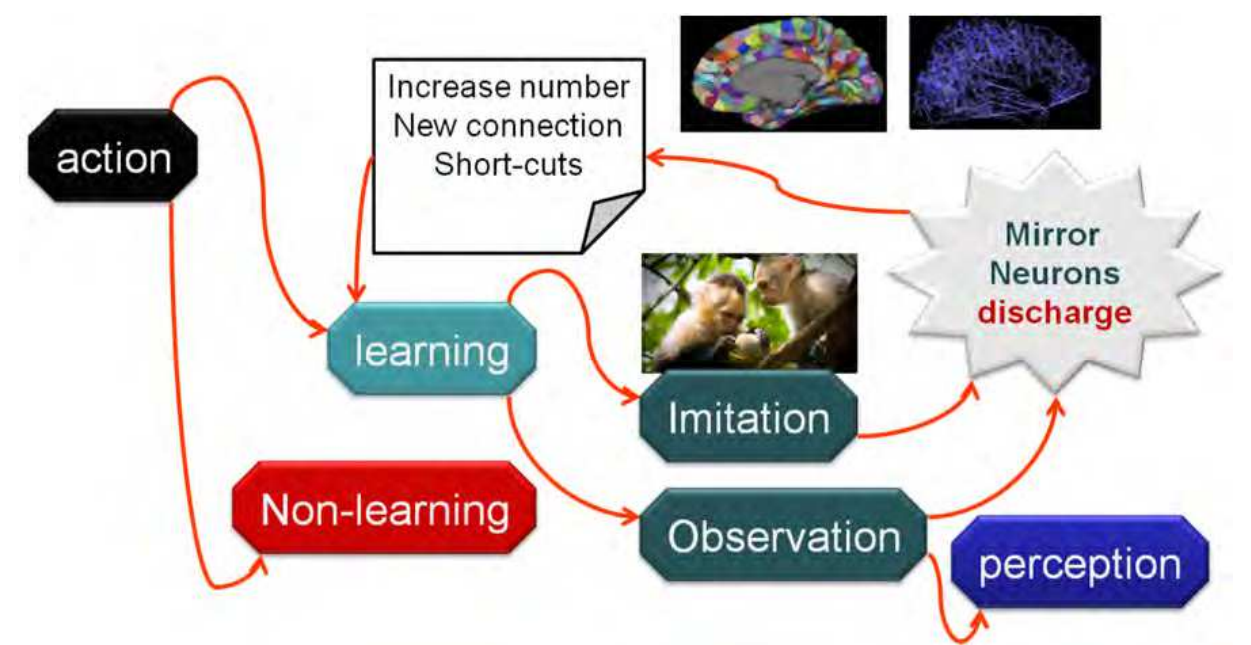


Fig. 2.6. Learning procedure of imaginal thinking

2.2.2.2 Non-learning procedure

Non-learning procedure, also called problem solving action, aims at finding the appropriate knowledge and experience to solve the demanding problem so as to meet biological desires and requirements. The detailed processes are shown in Figure 2.7.

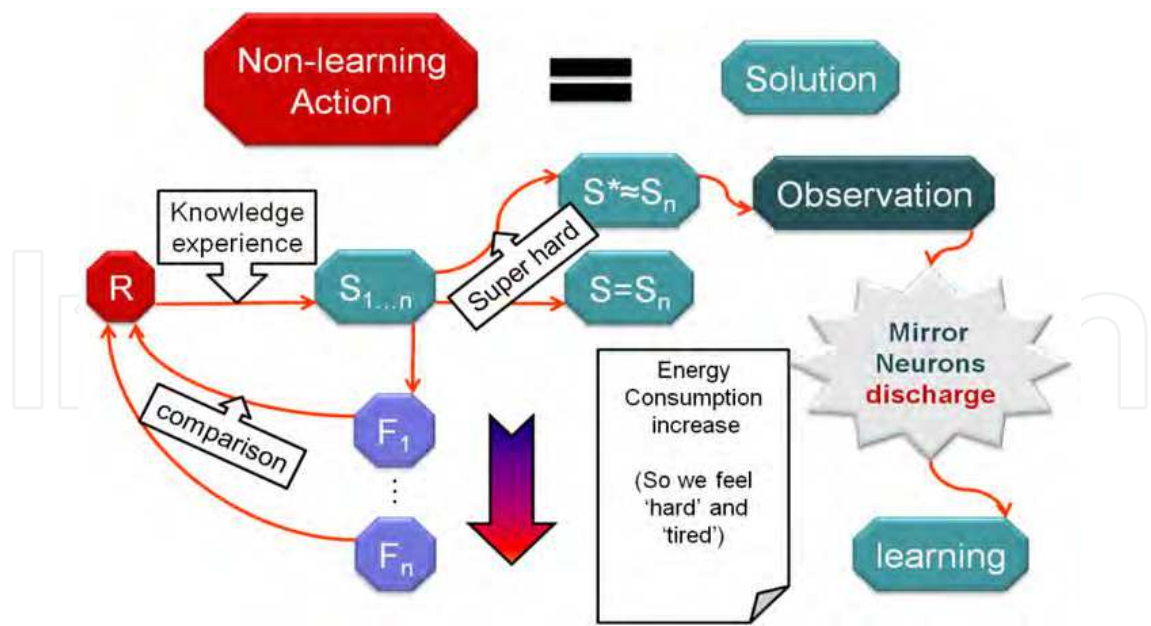


Fig. 2.7. Non-learning procedure

Survival instinct generates a requirement when humans perceive stimuli of outer or inner environment, which is denoted as R . By scanning the former knowledge and experience from low to high consumptive energy, a series of solutions are generated, denoted as S_1, \dots, S_n . Of course all the possible solutions can't be generated immediately, instead whenever a solution is obtained, human brain converts it to the potential function, denoted as F_1, \dots, F_n . Once a function is generated, human brain compares it with the previous requirement; if it fulfills the requirement, the corresponding solution will be the final solution, denoted as $S=S_n$. If all the solutions cannot satisfy the requirement, human brain will try to find the most closer solution as $S^*\approx S_n$, and apply the solution. At the same time humans observe the performance, which forms new neural synapses causing excitation of mirror neurons. Such procedure is similar as learning procedure which provides knowledge and experience for future tasks.

2.2.3 Imaginal thinking vs logical thinking

The symbolism emphasizes on logical thinking, the logic can be considered as a special type of high dimensional image in imaginal thinking frame. Such image is represented with mathematical logic procedures with each step still an imaginal thinking one, figure 2.8. So logical thinking can be considered as a certain level of imaginal thinking, namely a specific neural network level representing the mathematical logics, and the memory and knowledge lying in this network level are unexceptionally stored as high dimensional images. Therefore, logical thinking is a special type of imaginal thinking.

2.2.4 Imaginal thinking vs intuitive thinking

The connectionism emphasizes intuitive thinking which has no clear representation between the requirements and solution, only the result is respected. Actually, such procedure only happens when the searching of past knowledge and experience cannot meet the requirement, denoted as $S_{1...n} \neq S$, so the human brain goes for blind search trying to find a similar neural network pattern to solve the similar problem. Such procedure is searching for metaphors or

analogies. The searching continues until a sudden stimulus generates a neural network which meets the requirement, then human takes this solution to generate motion potential, denoted as $S^* \approx S$. It does not matter why this neural network results in a satisfactory solution, however what's really significant is to meet the survival requirements. Such thinking which cannot be represented by mathematical logic or existed knowledge or experience is intuitive thinking, the essence of which is still a special type of imaginal thinking.

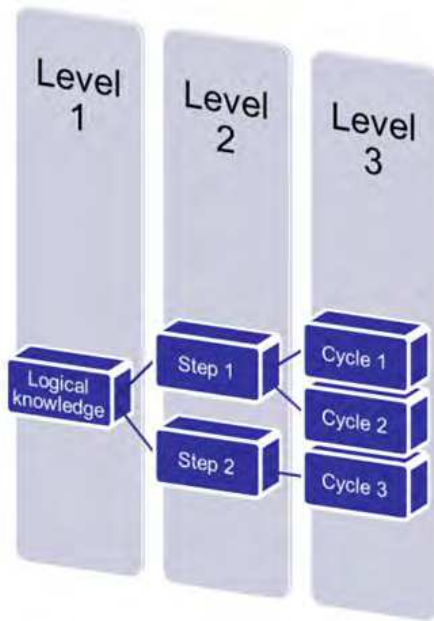


Fig. 2.8. Logical thinking structure

2.2.5 Role of imaginal thinking

As is shown in figure 2.9, behaviorism, characterized by a simple perception-action process, is a lower level of human thinking which is most common in initial development phase of human intelligence. The two basic elements of behaviorism, perception and action can be both denoted as images thus the whole procedure can be seen as transformation of one image to another to generate a satisfied image guiding the future action. Without image, the essential interaction between perception and action certainly doesn't exist, so a proper act is almost impossible to happen.

As humans interact more and more with outer environments trying to solve problems to meet desires and requirements, knowledge and experiences stored as high dimensional images are accumulated which lays a foundation for logical thinking favored by symbolism. This logic can be considered as a special type of high dimensional image in imaginal thinking. With ascending ability to reasoning and deducting and expanding knowledge and experience base, humans tend to handle more complicated problems. Sometimes past knowledge and experience cannot meet present requirement, as intuitive thinking accentuated by connectionism describes, human brain goes for blind search trying to find a similar neural network pattern to solve the similar problem. This process is actually finding the best matching of requirements and solutions both denoted by images, the innate logic is still based on past knowledge and experience represented by numerous images in human mind only this transformation of images isn't clear.

Thereby, as figure 2.9 shows, we can conclude that imaginal thinking actually includes the characteristics of all other thinking styles, logical thinking and intuitive thinking. It also solves the conflicts between different ideas and assumptions of artificial intelligence, symbolism, connectionism and behaviorism. Besides, neural functions and human thinking are bonded tight by imaginal thinking and it addresses the origin of human thinking from an aspect that none of the former theories has proposed. It's reasonable to reach the conclusion that imaginal thinking is fundamental to human thinking and can lead us into the truth of human thinking.

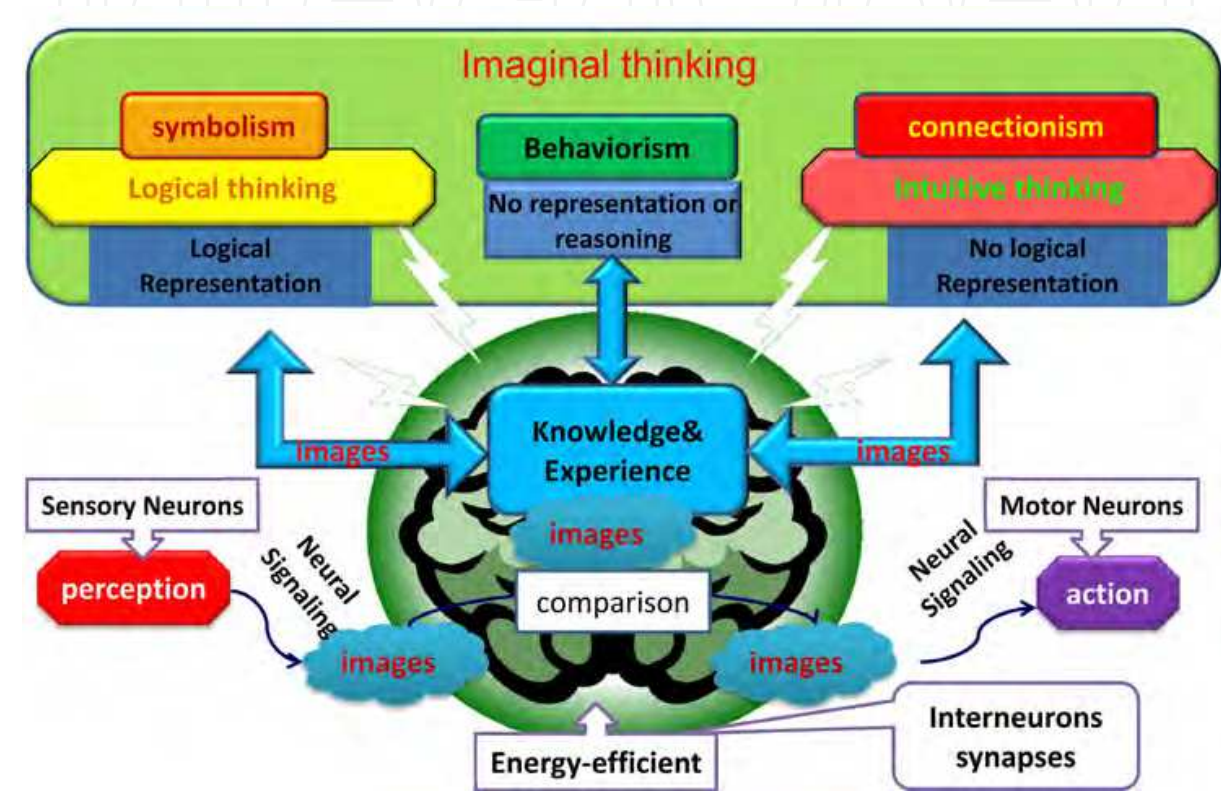


Fig. 2.9. relations between imaginal thinking and other thinking styles

3. A novel visible graph methodology integrating imaginal thinking

When faced with difficult engineering problem, lots of bio-inspired approaches, such as naturalistic biological synthesis approach and evolution inspired methodology have been tried and exhibited great advantage over traditional logical mathematic algorithms in improving system adaptability and robustness in uncertain or unpredictable situation^[12,13]. As for pipe-routing, a typical NP-hard problem in limited 3D space, experienced human brain is often capable of providing more reasonable solution within acceptable time than computer. In this section, we will present a novel design methodology of visible graph integrating human imaginal thinking.

3.1 human imaginal thinking in pipe-routing

Pipe-routing is actually far more complicated that it appears to be, not only it's a typical NP-hard problem in limited 3D space, but also most of it relies on human experience. Besides,

there exist strict restrictions in pipe-routing which can't be expressed by standard statistics. So experts' advice and opinions are totally indispensable in pipe-routing. The present platform in pipe-routing can't be fully self-dependent, instead people need to guide the whole design process based on their knowledge and experience.

Faced up with difficult engineering problems and math questions, experienced human mind always offers more practical solutions within limited and accepted time. It's important to notice that people recognize the whole pattern of pipe-routing through imaginal thinking. So if we want to get a smart pipe-routing system or a algorithm, we must first understand how humans recognize the whole space.

Human mind represents knowledge and experience by forming the holistic image of feasible workspace. This holistic image cognizing the layout of all pipes is achieved by decomposing, comparing and coordinating among the images which reflect human knowledge and experience. The experience includes pipe functions, piping order, manufacturability, vibration concerns and leakage protection, while knowledge consists of obstacle shape, pipe size, liquid velocity, temperature, thermal deformation, etc.

Firstly, a predetermined piping order is decided by human engineering experience: from inside to outside, from dense part to sparse part, from thick pipe to thin pipe, from short pipe to long pipe. The pipes locating on relative inner side are harder to replace and maintain due to the intervention of the covered pipes outside. Therefore, the pipes which need frequently replacement or maintenance should be arranged in outer layers which are easier to reach and manipulate. According to geometric knowledge, a geodesic line can be connected from the start point to the end point which shows the optimal path for each pipe. All the geodesic lines of pipes holistically form a path-net image which shows spatial density of the piping system. Human always deals with dense parts first while the sparse parts are left to behind, since that the pipe-routing is more complicated in dense parts due to smaller average free space, more obstacles and more complex constraints. The routes of thick pipes are always decided before the thin pipes, as the thick pipes are not as 'flexible' as thin pipes and are not allowed to be manufactured with many elbows.

Secondly, the effective obstacles and limitations along the geodesic line should be found for each pipe. The effective physical obstacles which consist of auxiliary equipments and other pipes are determined by checking whether these obstacles get in the way of geodesic line. In addition, virtual limitations of electric protection, deformation, temperature, vibration, etc are also taken into consideration. The pipes are divided into groups according to pipe functions, such as fuel, lubrication, gas, water, electrical signal. The pipes in the same group have similar virtual limitations. The effective physical obstacles and virtual limitations are dynamic, since they change with the different groups and pipes. All the requirements for routing each pipe are decomposed to a series of images of dynamic obstacles and limitations in human brain. By comparing those images to experience and knowledge, human acknowledges the perspective situation for each pipe respectively.

Finally, immediate coordination on those images of dynamic obstacles gets the holistic image of the pipe-routing problem. The images of dynamic obstacles and limitations are coordinated, which transfers all those intricate experience and knowledge into an easy distinguishable decision-making problem: feasible space or unfeasible space. Every piece of

human experience or knowledge is correlated to some unfeasible space with the rules in human mind. Such correlations can be considered as mapping the experience and knowledge to images representing the information of how to route the pipe. By recognizing the unfeasible space, the feasible space is achieved for each pipe. The finding path problem is consequently as same as finding the shortest path in the holistic feasible space which contains all the human experience and knowledge.

As we have understood every step in pipe-routing using imaginal thinking, we notice that human imaginal thinking in pipe-routing is direct, effective and intentional which is different from the blind computer-based route algorithm. Especially, imaginal thinking is characterized by images representing, converting and transferring information which guarantees high efficiency. Next, to combine the advantages of both human intelligence and computer's massive accurate calculation, we need to endow computer with human intelligence in pipe-routing.

The biggest obstacle for computer to imitate imaginal thinking is that the hardware is fundamentally different from the structure that enables human to react to outside environments. Computer has independent control, transport, memory parts. Output and input appliance are only connected by memory. So computer can only work according to programs and isn't able to learn and adapt to environment. Both the experiments on capuchin monkeys and the study on the social learning show solid evidences for the importance of imitation in learning. Thus it's highly reasonable to teach computer how to imitate and the knowledge computer can grab through imitation. Of course this needs a language that can be understood by computer, although we're restricted by the Von Neumann structure, this doesn't mean that imitation of human thinking is meaningless. Since it's impossible to render computer gain human-like neural network and study ability at present, we can help computer to imitate human thinking instead. Though every step is accomplished by humans rather than computer, like study function, variable structure ability, processing and etc, the whole imitation of thinking can make us get closer to real artificial intelligence. So next we will present the elaborate steps about how computer can imitate human thinking to obtain shortest path more efficiently.

3.2 Visible graph method based on imaginal thinking

Pipe-routing can be seen as searching for the pipe path meeting requirements in 3D space given starts and ends. Configuration space and visibility graph are common methods in path plan. In this part we will present a novel visibility graph based on human imaginal thinking to lower computation complexity of traditional visibility graph and increase efficiency. Euclidean Shortest Path—ESP is a famous NP problem which can be defined as searching for a path avoiding all obstacles given two points S, T and a set of obstacles in Euclidean space. Shortest path in 3D space have been paid much attention since 1970s, in this article, we mainly concentrate on situation where obstacles are mainly convex polyhedrons. Lots of algorithms have been put up, from which we can conclude that two basic questions in obtaining shortest path in 3D space: finding possible edge sequences that optimal path can travel along and determining the shortest path on edge sequences are coupling. How to handle this problem effectively is crucial to construct an efficient shortest path algorithm. In the rest of this part, we will give detailed procedures of refined visible graph method integrating imaginal thinking.

3.2.1 Design of feasible workspace

Aero-engine pipe routing can be seen as searching for the path meeting obstacle restrictions given the starts and ends of pipes. All restrictions can be classified as physical obstacles and virtual obstacles. The physical obstacles include equipments, auxiliaries and other pipes; while the virtual limitations consist of manufacture, installation, maintenance requirements, or manual pipe function divisions and area divisions, or vibration and thermal deformation. The physical obstacles are easy to be represented as 3D images because they actually exist. With the vertices of each obstacle, convex hull can be calculated in polynomial time to represent the space that the obstacle covers. Concave obstacles can be decomposed as a union of several polyhedral. Every obstacle can be denoted as an unfeasible space by U_p^i where p represents the physical obstacle and i denotes ith obstacle.

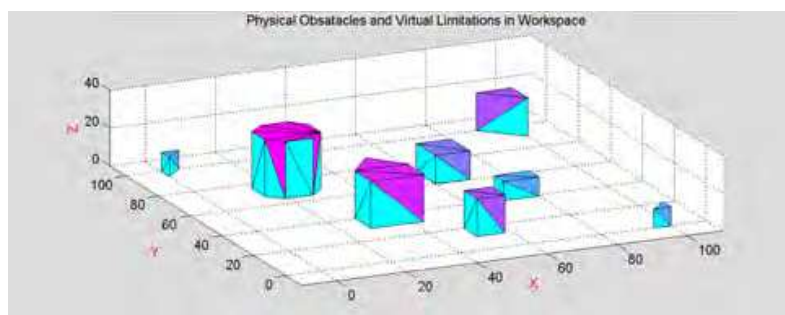


Fig. 3.1. physical obstacles and virtual limitations in workspace

The virtual limitations need to be represented as visible images based on either human experience or engineering knowledge. Although they are invisible, the invisible limitations need to be transferred to visible unfeasible workspaces. Taking electric protection as an example, the water pipes should be nowhere around the electric auxiliaries in case the malfunction caused by leakage. Then the space that encloses the electric parts is considered as one kind of unfeasible space for those water pipes, also denoted as visible unfeasible space U_v^j , where v represents the virtual and j denotes jth limitation. Due to the limit of the chapter length, we cannot list all the procedures of transferring the experience to unfeasible spaces, although different experience and knowledge have their distinct methods to be represented as images.

With all the physical obstacles and the virtual limitations denoted as a closed set and U^j , if we assume the whole workspace as S, and the feasible workspace F_k for the kth pipe is expressed by Eq. (1):

$$F_k = S - \sum_i U_p^i - \sum_j U_v^j \quad (1)$$

The feasible workspace F_k is also dynamic for each pipe since each pipe has different $\{U_p^i\}$ and $\{U_v^j\}$. Fig 3.1 shows the 3D explanation of the feasible space F_k for one pipe. The array $\{F_k\}$ forms a holistic image which not only makes human experience and knowledge visible but also represents human perspective concept in system design. By overlapping the images of the feasible workspaces of all the pipes represented as $\{F_k\}$, the holistic layout of all pipes

is obtained. The pipe system design is based on such layout by routing the pipe with predetermined pipe order.

3.2.2 Decomposing global information for each pipe to generate local images

When planning a route for each pipe according to the pipe order, human also uses global concept to route. The computer route-planning algorithms in next section are conceived by imitating such human behavior. The optimal path for each pipe is decided by decomposing its feasible workspace to local images, comparing the local images, and coordinating the possible routes.

The holistic image of feasible workspace $\{F_k\}$ needs to be modified by imitating human knowledge of interference of the pipe size. Human sees all the unfeasible space with an offset boundary according to the pipe size to be routed. Such boundary ensures no physical conflicts between the obstacle and the pipe. The modification is virtually shrinking the pipe to its centre line and growing all the obstacles with the pipe size. Therefore, among several existing methods, we here apply translational configuration space obstacle (TCSO) to the feasible workspace $\{F_k\}$ to generate modified $\{F_k\}$ which imitates the human thinking in forming images of obstacles with pipe size [14]. Fig. 3.2 shows the image of obstacles modified with TCSO.

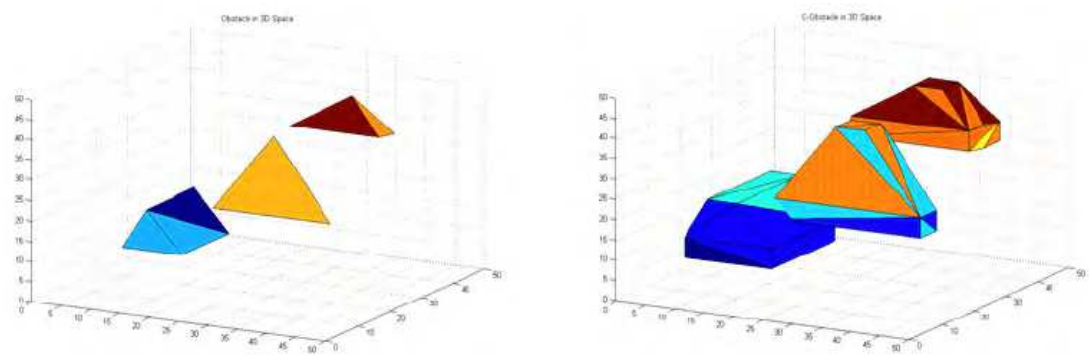


Fig. 3.2. Translational configuration space obstacles with pipe dia.5

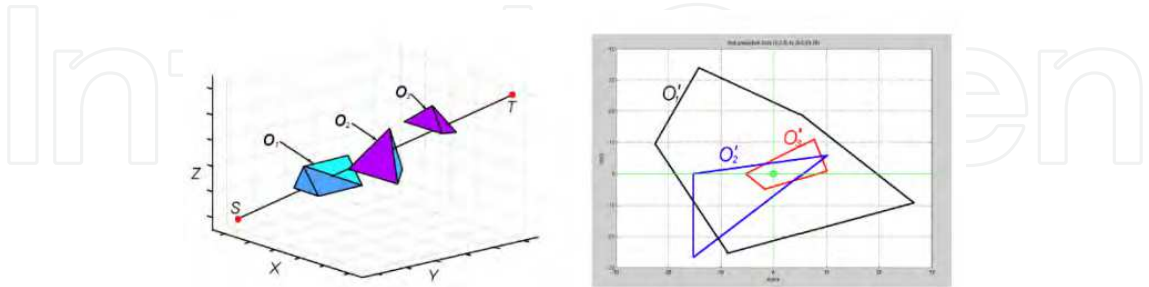


Fig. 3.3. 2D Projection of 3D Convex Obstacles

It has been proved that the shortest path connecting the start point S and the termination point T avoiding all the convex obstacles is through the obstacle edges in 3D case. When the global information is not available, human has to make decisions based on what can be seen at the present position. From one edge to the next, human only goes to those visible edges. Therefore, the visible graph is the method to generate the candidate edge sequences for the

shortest path. Each modified feasible workspace F_k needs to be further decomposed to a series images to describe what human sees along the global routing direction. fig 3.3 describes three obstacles in 3D space and their first projection from start S to destination T.

The traditional visible graph uses computer logic that generates all the visible nodes or edges on the obstacle considered to be possible nodes or edges, while a lot of which are never seemed to be the candidate for the shortest path. By imitating human global optimal routing concept, we here improve the visible graph to find only the reasonable candidate nodes or edges through the path and delete as many the redundant nodes or edges as possible, so as to shorten the calculation time.

The 3D visible graph expresses the visibility among edges of polyhedral by connecting all the edge pair that sees each other fully or partially without blocks in between. The visibility is determined by comparing a series projected images which show 2D explanation of 3D information. The images in projection plane are polygons, therefore only the vertices need to be transformed. The projection of a polyhedron is received by projecting the vertices of the polyhedron to the image plane. This image plane is perpendicular to the direction from the initial projecting node to the termination node. The projected polyhedral images are used to produce the visible edges for a single node. After the projection, the obstacle space coordinates are transformed to image plane coordinates, a transform matrix ensures the collineation. The collineation provides a proper way to project vertices from the 3D space to the 2D image planes. The outline of the image can be obtained by connecting the appropriate vertices using the theorem.

Theorem 1: Given an object space R and an image plane R', let a convex polyhedron O_i be projected onto R' as O_i' by collineation. Then the outline of O_i' forms a closed edge loop on O_i [15].

3.2.3 Comparing among the local images to generate edge sequences

In 3D feasible workspace, as the shortest path only exists along some of the edges of the convex polyhedra obstacles, the main purpose of comparing the visible graph is to find the visible relationship between edges. The four rules to find the reasonable candidate nodes or edges through the path and delete all the redundant nodes or edges are as follows:

Rule 1: Only the polyhedra in $\{U_p^i\}$ and $\{U^j\}$ that block the direction from the start point S to the termination point T are taken into account as obstacles of visible graph. Human only considers the blocks that are in the way as the obstacles.

Rule 2: If the termination point T is visible from any edge, then the termination point will be the only visible point for this edge, any other edges are no longer considered as visible. Human goes directly to the destination from any position and never goes to intermedial points if the direct path is accessible.

Rule 3: If any edge sees an edge that has been seen by its ancestor edges before, then this edge is considered as invisible. Human avoids the points that have been reached before and only goes to those points have not been attempted.

Rule 4: For each visible edge, if on the different positions along the edge, the visible sub-edges are different; this edge has to be further divided into several segments to replace the

original edge, by viewing from the termination point T to the edge according to the obstacles in between.

On the basis of visible graph, the edge sequences in 3D can be achieved as shown in Fig. 3.2, by representing as edge sequence tree. Every possible route is one branch from the root (the start point S) to the leaf (the termination point T).

3.2.4 Coordinating the edge sequence tree to obtain optimal path

The local shortest path via every branch of the edge sequence tree needs to be locally optimized first. After all the local shortest paths are specified, the global optimal route is chosen by comparing the lengths of the routes.

Theorem 2 :In 3D space distributed with convex polyhedra, the shortest path between two points has the property that if it turns on an edge, the angles formed by two adjacent path segments and the edge subtend. (Due to length of this chapter, the detailed proof of the widely accepted [Theorem 1] and [Theorem 2] is omitted here; similar proof may be found in Mitchell's survey paper [15])

Local optimization is based on Theorem 2 with following procedures:

Firstly, checking each edge sequence, if the equal diagonal angle condition cannot satisfy on any edge by adjusting three related turning points, discard the sequence.

Secondly, for those possible sequences, as shown in Fig. 3.4, calculate the turning point T_1 on E_1 . Based on start point S and the middle point M_1 of E_2 , the diagonal equation $a_1 = b_1$ should be satisfied. Unfold the two triangle plane formed with the four points (vertices of E_1 , S and midpoint on E_2) into the same plane then connect S to M_1 with a line. This line either intercrosse the edge E_1 in its visible range, or at one end of the range closer to $a_1 = b_1$ (in case the range is not long enough). Find the visible range of E_2 , from the new turning point on E_1 and the middle point on E_3 , adjust the turning point on E_2 . Carrying on the process until the turning point on E_n is adjusted.

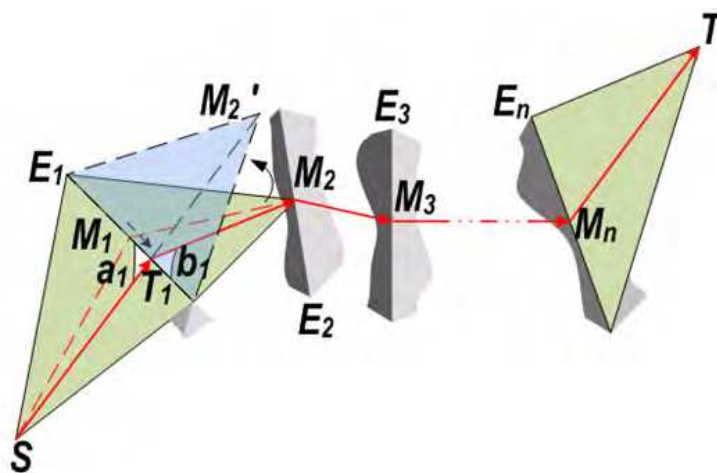


Fig. 3.4. Adjusting the edge sequence in the turning points

Thirdly, repeat the second process to adjust the turning points from E_1 to E_n several times. After i times, the comparative error δ will be within a certain amount ε , where $\delta = |l - l|$

$_{i+1})/l_i| \leq \epsilon$, l_i is the length of the path at i th computation. Then the path image formed by the representing links is the shortest path via this edge sequence with certain precision.

With all the local shortest path images being determined considering the experience and knowledge represented in feasible workspace, the global optimization is mainly computational comparison by selecting the global shortest path from the local shortest paths via different edge sequences. This process is a typical logical thinking, since there is no better way rather than accurate calculation to select the best path from all the possible candidates, and obviously computer does this much more efficient than human.

It's obvious that after introduction of some rules imitating human thinking, visible graph method integrating imaginal thinking reduces the complexity of computation and can obtain optimal path more efficiently. So searching for optimal path in 3D space, a highly logical process can be successfully represented by processing of high-dimensional images as mentioned in former section. This proves imaginal thinking is basically a fundamental style reflected by other thinking styles. Besides although refined visible graph method is presented under the circumstances of pipe-routing, it's also applicable in path plan for robot and printing circuit board (PCB) planning.

4. Pipe-routing algorithm by imitating imaginal thinking

In this part, human's imaginal thinking is further simulated with procedures of knowledge representation, pattern recognition, and logical deduction; the algorithm transforms the physical obstacles and constraints into 3D pipe routing space and then into 2D planar projection, by using convex hull algorithm onto the projection, the shortest pipe route is found efficiently. The pipe-routing algorithm by imitating human imaginal thinking is then obtained, which effectively solved the problem of conceiving the shortest pipe route in 3D space with obstacles and constraints.

4.1 Overview of algorithms concerning pipe-routing

Pipe assembly planning is a problem, which very much relies on a pipe routing algorithm that decides the pipe paths and affects the pipe assembly feasibility. Pipe routing algorithm has been a popular research field in the past several decades in different industrial applications, such as printing circuit board (PCB) planning, chemical plant layout, ship pipe system design, and aero-engine pipe route design. The pipe routing problem can be generally defined as the problem of planning the shortest path connecting two ends of the pipe in a limited workspace by avoiding all obstacles with the given pipe size for each pipe, meanwhile considering all the constraints that affect the pipe system. Much effort has been put into creating new algorithms and improving the efficiency of the existing ones.

The maze algorithm presented by Lee (1961)^[16] was the earliest research in pipe routing problems. The algorithm was developed to find the shortest path in logical electronic circuit design (Lee, 1961). The workspace was meshed into units, and the algorithm was based on wave propagation principle. Each path was found by generating a wave from the start unit and propagating through all the meshed units until the wave reaches the end unit. The maze algorithm requires massive memory space to find the shortest path of each single pipe in 2D space, since every single meshed unit has to be covered. The computational complexity of the maze algorithm in 2D space is $O(n^2)$, where n represents the problem scale such as

number of meshed units. To improve the efficiency of the maze algorithm, Hightower (1969)^[17] introduced an escape algorithm by using two orthogonal lines instead of wave propagation which was widely used in PCB design. Although the escape algorithm used less memory space than the maze algorithm, it does not guarantee to find the shortest path even if sometimes the path is quite obvious. Wangdahl et al. (1974)^[18] improved the escape algorithm by defining intervisible points and intervisible lines to guide the escape lines so as to find the shortest connection to avoid obstacles. This kind of algorithm, known as network optimization, needs experts to define such nodes that pipes intercross, connect, and swerve, therefore, the pipe routing results depend very much on human's experiences. Zhu ^[19] and Latombe (1991) proposed a pipe routing algorithm by transferring the pipe routing problem into robot route planning with several constraints; whereas the algorithm has to backtrack when it fails to find a channel for the "robot." The genetic algorithm (GA) was first applied into pipe routing problem by Ito (1999, 1998)^[20,21] in 2D space with satisfactory results. Ito's algorithm used single and two-point crossover which led to lots of unacceptable solutions. Adaptive genetic algorithm (AGA) was developed to comprise the contradiction between diversity and convergence of traditional GA. By use of adaptive probabilities of crossover and mutation, AGA realized the twin goals of maintaining diversity and sustaining the convergence capacity (Srinivas and Patnaik, 1994). Simulated annealing GA is another adaptive GA which was applied in ship pipe system design with suboptimum results (Fan et al., 2007a). GA is robust and random, however, different definition and rule of fitness functions yields different solutions, some of which are far not optimal. By research on ant social behavior, ant colony optimization (ACO) was introduced into industrial applications as revolutionary computation method by Dorigo et al. (1996) and Bonabeau et al. (2000). To overcome the deficiency of cooperation in GA, ACO was applied in ship pipe route planning with better results comparing to GA (Fan et al., 2007b). Fuzzy function (Wu et al., 1998) and expert system (Kang et al., 1999) are two tools used to extend the limitation of the existed automated pipe routing computer-aided design systems. Although attempts have been made to provide the pipe routing problem with reasonable solutions, more work is still needed before real breakthrough.

All the above algorithms focus on avoiding physical obstacles, and pipe routes are calculated in orthogonal directions which are not theoretically shortest. Practical constraints such as maintenance requirements and manufacturability are not well recognized, consequently human still cannot be replaced by computer and human is still needed to guide computer to complete the design.

4.2 Knowledge representation

4.2.1 Workspace definition

Human imaginal thinking is limited to R^3 space and tends to use 2D graphs to display 3D information. Most of the complicated workspace shapes can be divided into two main kinds: cubic and cylindrical. In the cubic space, such as chemical plant, PCB, and indoor pipe systems, coordinates can be defined easily by using orthogonal (x, y, z) coordinates which are parallel to the cubic edges. In the cylindrical space, such as sub-marine, aero-engine, and coordinates can be defined as (θ , r, h) cylindrical frame. With equation (1), the absolute (x, y, z) coordinates can be achieved, and the coordinate definition is shown in Figure 4.1:

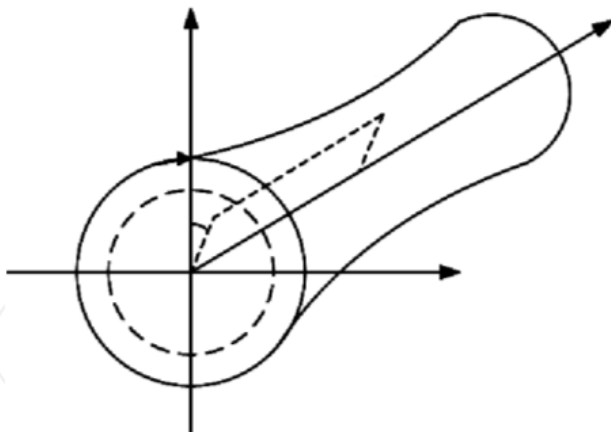


Fig. 4.1. Cylindrical coordinate definition

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r \cdot \cos \theta \\ r \cdot \sin \theta \\ h \end{bmatrix} \tag{1}$$

The cylindrical space can be unrolled to cubic space as shown in Figure 4.2 which is similar to the correspondence between the globe and the 2D world map. By unrolling the cylinder, the 3D pipe route is calculated in the cubic space which is easy for meshing and projection.

The above definition is universal to most the algorithms, therefore different algorithms can be applied to the same model.

4.2.2 3D inaccessible space definition

By defining the inaccessible space, the accessible space is achieved for each pipe. Every constraint is converted into an inaccessible space, which reflects real physical obstacles and hypothetic limitations. The real physical obstacles include equipments, auxiliaries, and other pipes; while the hypothetic limitations consist of manufacture, installation, maintenance requirements, or manual pipe level divisions and area divisions, or vibration and thermal deformation. Every inaccessible space is denoted as a closed set U_i where I denote different constraint and the accessible space F for each pipe yields by equation (2). Figure 4.2 shows the 2D explanation of the inaccessible spaces:

$$F = \overline{U_1 \cup U_2 \cup U_3 \cup \dots U_i \dots \cup U_n} \tag{2}$$

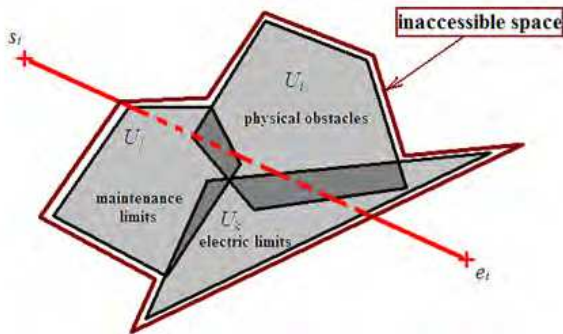


Fig. 4.2. Generalized inaccessible space

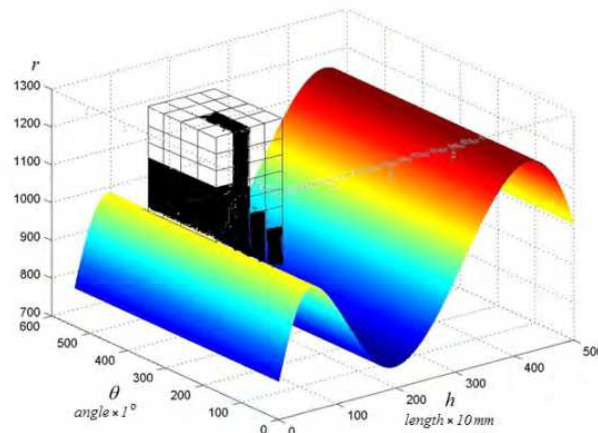


Fig. 4.3. 3D inaccessible space division

In practical use, the cubic space is meshed with cubic unit ($d\theta$, dr , dh), and every cube has two statuses: accessible and inaccessible which are denoted as “0” and “1.” As shown in Figure 4.3, white cubes denote “0” indicating accessible and black cubes denote “1” indicating inaccessible.

For each ($d\theta$, dh), sum up all the continuous accessible cubes along r direction, and the max accessible width vertically is denoted with 1. If the pipe diameter is d , when $\varepsilon < d$, set the corresponding grid in 2D pipe map as inaccessible; when $\varepsilon \geq d$, set the corresponding grid in 2D pipe map as accessible. All the 3D constraint information is expressed in the 2D pipe map. In addition, pipe system always designed as several layer divisions. Each layer can be also projected to the pipe map as shown in Figure 4.4.

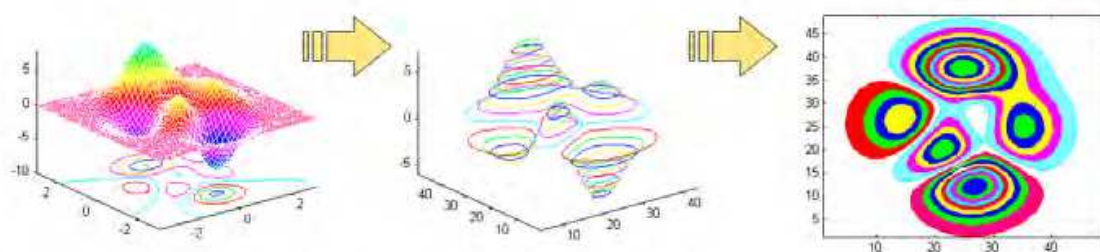


Fig. 4.4. 2D projection of pipe layer division

4.3 Pattern representation

4.3.1 Pipe routes density recognition

When human designs a pipe system, a predetermined piping order is decided by experience, which is from inside to outside, from dense part to sparse part, thick pipe to thin pipe, short pipe to long pipe. These long-time accumulated experiences, lacking an accurate reasoning and deduction process, can be best represented by intuitive thinking style emphasized by connectionism. As is mentioned in 1.2.4, we believe intuitive thinking is actually a special kind of imaginal thinking. From the following analysis, we will find these spontaneous thoughts in pipe-routing can be represented by images to solve problems. Here, follows elaborate justification and explanation of the experienced order chose rules.

4.3.1.1 Inside to outside

The pipe routing space, no matter cubic space or cylinder space, can always find a direction which points from inside layers to outside layers and the pipes are routed on respective layers. The pipe lies on relative inner layers are harder to replace and maintain due to the intervention of the covered pipes in outer layers. Therefore, the pipes which need frequently replacement or maintenance should be arranged in outer layers which are easier to reach and manipulate. Pipes on inner layers are those need little replacement.

4.3.1.2 Dense to sparse

Within one pipe layer, the positions of starts and ends of pipes determine the pipes locations. A skillful pipe route design engineer always deals with dense pipe intercrossing parts first while the sparse parts are left to the end, that is because in those dense parts, pipes have to share not only the free routing space but also the obstacles and the constraints of each pipe, which interferes with each other. This makes the pipe routing more complicated in dense parts due to smaller average free space, more obstacles and more complex constraints. The route design of the pipe in sparse part is relatively easy since each pipe has bigger free routing space to travel and less obstacles to bypass.

4.3.1.3 Thick to thin, short to long

Pipe diameter is another key parameter in pipe routing order chosen. The routes of thick pipes are always decided before the thin ones. The main reason for this is because the thick pipes are not as "flexible" as thin pipes which means thick pipes are not allowed to manufacture to the shape of many elbows. The gap between each pair of adjacent elbows has a minimum length of straight pipe. The lack of flexibility of the thick pipe makes it harder to conceive the path from the start

point to the end point than those thin ones. Another reason for designing the routes of thin pipes after the thick ones is that the thin pipe can be fixed along the thick pipes which are installed already, so the routes of thin pipes somehow decided by the thick pipes installed before them. The lengths of pipes are the last order chosen parameter of those pipes with same diameter. Similarly, short pipes are always preferential to long pipe due to smaller numbers of possible elbows along the way. The order chosen of the pipe with human experience is recognized by computer as follows.

4.3.1.4 Inside to outside

Divide the works pace to $n+1$ layers along the vertical direction r or z , the lower and upper boundaries are denoted as: $[r_{inner}, r_1), [r_1, r_2), [r_2, r_3), \dots, [r_{n-1}, r_n), [r_n, r_{outer})$ (2)

Where:

$$r_{inner} < r_1 < r_2 < r_3 < \dots < r_{n-1} < r_n < r_{outer}$$

Define every layer from inside to outside as $L_1, L_2, L_3, \dots, L_{n-1}, L_n, L_{n+1}$; sort the pipe by its replacement time; assign the pipe with long replacement time to inner layer and the pipe with short replacement time to outer layer. Every pipe is assigned to a layer and every layer contains a group of pipe(s). When pipe routing, the inner layer is prior to outer layer.

4.3.1.5 Dense to sparse

For each layer L_i , connect the start point s_i and the end point e_i of the each pipe with geodesic lines (explain below), ignoring all the obstacles. By using output sensitive balanced binary search tree algorithm (de Berg et al., 2005)^[22], the intersections of lines are obtained. Use a sweep line l scans the pipe map along the increasing directions of θ (or x) or h (or y). The lines that intercross the sweep line l are stored in one of the leaves of balanced binary search tree T . By inputting starts set, all the intersections and the relevant lines are achieved.

Mesh the pipe map along (θ, h) or (x, y) , set the mesh grid as maximum diameter of the pipe in such layer $d\theta=dh=3 \cdot D_{max}$, where D_{max} is the maximum diameter. Every start, end and intersection locates in a grid of $(d\theta, dh)$ or (dx, dy) . Number the grid by the quantity of the starts, ends, and intersections of the lines. The grid with bigger number contains more pipes, as shown in Figure 4.5. The dense area is prior than the sparse area.

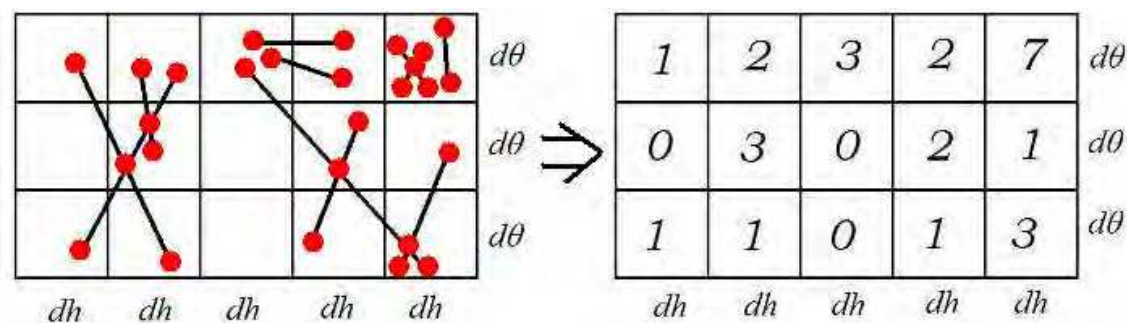


Fig. 4.5. Pipe density division in the same layer

4.3.1.6 Thick to thin, short to long

For same density area in a layer, pipe with bigger diameter is preferred and the pipe with thin diameter route along the thick pipes and clamped to the thick pipe. For same diameter pipes, the shorter pipe is prior to longer ones. The so-called shorter pipe is defined as pipe with shorter line connecting start and end points. Diameters of pipes and lengths of lines connecting start and end points are the last factordetermining pipe order. Diameters and lengths of pipes are display quantitative index, as for which human thinking and logic of computer have no difference.

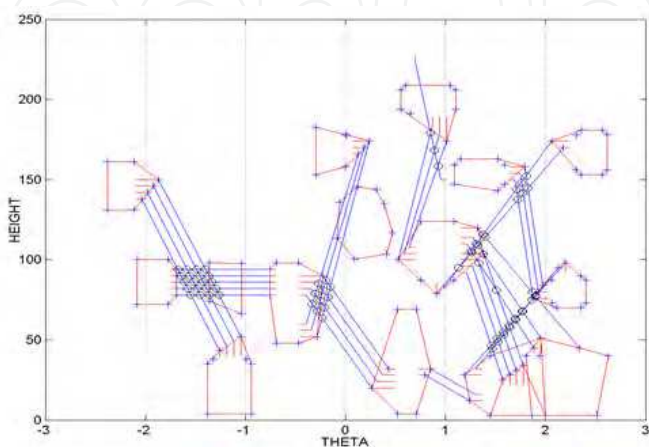


Fig. 4.6. Pipe density area

Figure 4.6 shows the actual application of these rules. Where red closed curves represent obstacles, blue cross dots symbolize vertexes of obstacles, blue crossing are geodesic lines connecting start and end points, blue circle dots are interaction points of pipe paths.



Fig. 4.7. the shortest path on the surface: geodesic line

4.3.2 Geodesic line

It is known from knowledge of differential geometry that the shortest path connecting two points on a curved plane is called the geodesic line. As shown in Figure 4.7, the flying trace of plane is the geodesic line of the earth which is the shortest path though it looks like a curve on the planar map. So, when bypassing obstacles in the workspace, the pipe should follow or as close as possible to the geodesic line so as to find the shortest route. As for the revolved surface, the geodesic line can be expressed as equation (4):

$$\int_{\theta_0}^{\theta} d\theta = \int_{h_0}^h \frac{c\sqrt{r_i'^2(h)+1}}{r_i(h)\sqrt{r_i^2(h)-c^2}}dh \tag{4}$$

where: $r_i(h)$ the rotational meridian. c the constant.

4.4 Logical deduction

4.4.1 Pipe routing

With the pipe map and the pipe orders in hand, the remaining pipe route concerns finding shortest path bypassing inaccessible spaces in 2D feasible workspace.

The simplest situation is shown as Figure 4.8(a) that the geodesic line penetrates one closed inaccessible space, and the pipe routing algorithm is as follows:

Algorithm Shortest Path (s_i, e_i, Ob_i)
Input. Start point s_i , end point e_i , collection of obstacles Ob_i
Output. Shortest path connecting start and end points
<div><div>1.</div><div>Connect start s_i and end e_i of the pipe with geodesic line, and mark entrance point and exit point of the inaccessible space U_i on the geodesic line as $k_1(\theta_{k1}, h_{k1}), k_2(\theta_{k2}, h_{k2})$</div></div> <div><div>2.</div><div>mark the midpoint of k_1, k_2 as $k_{1,2} \cdot (((\theta_{k1} + \theta_{k2})/2, ((h_{k1} + h_{k2})/2))$</div></div> <div><div>3.</div><div>$k_{1,2}$ is obviously an inner point of inaccessible space U_i; put all the adjacent points inside U_i in closed set K.</div></div> <div><div>4.</div><div>Apply convex hull algorithm (explained below) on set K so that the boundary of the inaccessible space U_i is obtained and denoted as convex set B.</div></div> <div><div>5.</div><div>Apply convex hull algorithm to $B \cup s_i \cup e_i$ again to get the following points sequence: $P = [s_i, p_1, p_2, p_3, \dots, p_n, e_i, p_{n+1}, \dots]$, where the sub-sequence from s_i to e_i is the shortest path bypassing the inaccessible space U_i</div></div> <div><div>6.</div><div>Return P'</div></div>

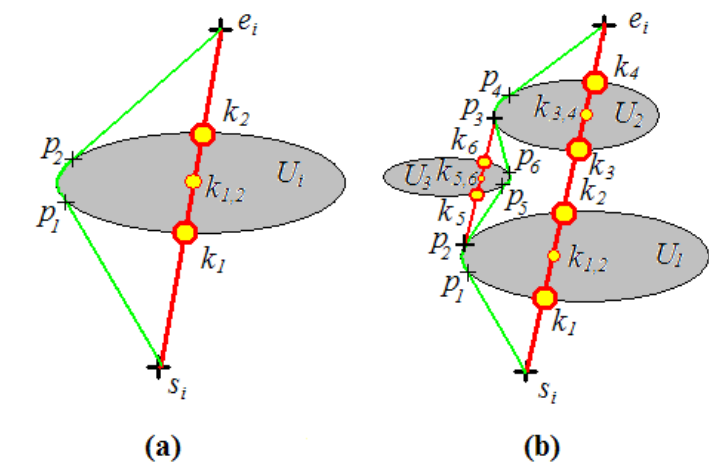


Fig. 4.8. Planar convex hull shortest path algorithm

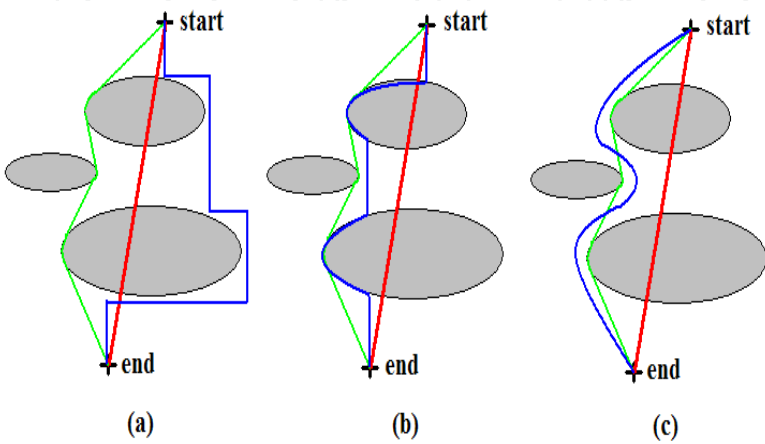


Fig. 4.9. The shortest pipe route

A more complicated situation is that the geodesic line penetrates several closed inaccessible spaces as shown in Figure 4.9(b). The pipe routing algorithm for this situation can be expressed as follows:

Algorithm Shortest Path (s_i, e_i, Obi)	
Input. Start point s_i , end point e_i , collection of obstacles Obi	
Output. Shortest path connecting start and end points	
Connect start s_i and end e_i of the pipe with geodesic line, and mark all the entrance points and exit points of every inaccessible space $U_1, U_2, U_3, \dots, U_n$ $k_1(\theta_{k1}, h_{k1}), k_2(\theta_{k2}, h_{k2}),$ $k_3(\theta_{k3}, h_{k3}), k_4(\theta_{k4}, h_{k4}),$ on the geodesic line as: ... $k_{2n-1}(\theta_{k2n-1}, h_{k2n-1}), k_{2n}(\theta_{k2n}, h_{k2n})$ totally n pairs of points where n denotes the number the inaccessible spaces.	
7.	Calculate all the midpoints of each pair of points and denote as: $k_{1,2}(\frac{\theta_{k1} + \theta_{k2}}{2}, \frac{h_{k1} + h_{k2}}{2}),$ $k_{3,4}(\frac{\theta_{k3} + \theta_{k4}}{2}, \frac{h_{k3} + h_{k4}}{2}),$... $k_{2n-1,2n}(\frac{\theta_{k2n-1} + \theta_{k2n}}{2}, \frac{h_{k2n-1} + h_{k2n}}{2}),$
8.	All the midpoints are obviously the inner points of inaccessible space $U_1, U_2, U_3, \dots, U_n$; put all the adjacent point inside $U_1, U_2, U_3, \dots, U_n$ in closed set matrix: [$K_1, K_2, K_3, \dots, K_n$]
9.	Apply convex hull algorithm on set matrix [$K_1, K_2, K_3, \dots, K_n$] so that the boundary of the inaccessible space $U_1, U_2, U_3, \dots, U_n$ is obtained and denoted as convex set matrix: [$B_1, B_2, B_3, \dots, B_n$]
10.	Apply convex hull algorithm to $B_1 \cup B_2 \cup B_3 \cup \dots \cup B_n \cup s_i \cup e_i$ again to get the following points sequence: $P = [s_i, p_1, p_2, p_3, \dots, p_n, e_i, p_{n+1}, \dots]$
11.	Extract the sub-sequence from s_i to e_i out of sequence P, in which every pair of points that enters and exits each inaccessible space can be found; together with the pipe start and end points s_i to e_i , form a new sequence denote as: $P' = [s_i, p_1, p_2, p_3, p_4, \dots, p_{2n-1}, p_{2n}, e_i]$ where p_1, p_2, p_{2n} are the n pairs of entrances and exits as shown in Figure 3.9(b).
12.	Extract : $p_2(\theta_{p2}, h_{p2}), p_3(\theta_{p3}, h_{p3}),$ $p_4(\theta_{p4}, h_{p4}), p_5(\theta_{p5}, h_{p5}),$... $p_{2n-2}(\theta_{p2n-2}, h_{p2n-2}), p_{2n-1}(\theta_{p2n-1}, h_{p2n-1})$ totally n-1 pairs of points, as new pipe starts and ends to repeat Steps 1-6 until no inaccessible space is penetrated.

As shown in Figure 4.9, the route from s_i to e_i which bypasses the inaccessible areas is the final path. Comparing with orthogonal route, polygonal route and curved route calculated by other algorithms as shown in Figure 4.9 (a)-(c), respectively, the geodesic route generated by this chapter is shorter; in addition, the routing algorithm proposed by this chapter starts with shortest geodesic line and bypasses every inaccessible space with length incensement as short as possible, therefore the obtained pipe route is the shortest path.

The algorithm conducted in this chapter imitates human thinking, which is with low-computational complexity of $O(n \log n)$ where n is the scale of the problem. The computational complexity of Step 1 that calculates the intersection points with the inaccessible spaces is no bigger than $O(n)$; the computational complexity of Step 2 that generates the midpoints and boundaries of the inaccessible spaces is also less than $O(n)$; the computational complexity is determined by the convex hull algorithm which is less than $O(n \log n)$ (de Berg *et al.*, 2005).

In this section, through imitation of human thinking, we use images to serve as medium of information to propose a 3D pipe-routing algorithm based on human imaginal thinking. From the above procedures filled with human experiences guiding pipe-routing which reflect intuitive thinking underscored by connectionism, we can see intuitive thinking styles can be presented with processing of images. Thus in turn our conclusion that essence of intuitive thinking is imaginal thinking is confirmed.

5. Simulation platform of pipe routing in aero-engine

During the design of pipes of aero-engine, various subjects like mathematical modeling, arrangement algorithm, static and dynamic strength, fluid, vibration and noise and fluid structure interaction are involved. These fields will use respective simulation software during the design and simulation process and tons of data will be generated. The data needs to be circulated frequently between design and simulation process to fulfill the goal that design offers information to analysis and in turn analysis amends design. However, the present data generated by design can only be used by manufacturing and assembly rather than simulation platforms; the results gained by simulation are mainly transformed into feedback manually which means the efficiency is very low. In a word, we lack a comprehensive design and simulation platform to do integrated management about the design tools, design process, simulation tools, data and simulation process.

In this part, we will introduce a platform suitable for design and simulation of aero-engine pipes, build advisable pipe design and assessment system, to let different design departments complete simulation and assessment of aero-engine pipes more efficiently and achieve optimization of pipe system; at the same time, we will consider comprehensively the practicability, routing ability, maintenance, reliability (including vibration check and strength check), durability and various design factors to construct proper pipe design and check system. So we can complete the simulation, assessment and check of aero-engine pipe system faster and more efficiently.

5.1 Problem description

Aero-engine is the "heart" of a plane determining the carrying capacity and performance of an aircraft. According to the accident reports on aircraft engines such as CF6 and CFM56 of

general electric, half of the engine accidents in the air are caused by pipe system and accessory system. The pipe system design of aircraft engine is extraordinarily difficult since the design is mostly based on human experience and knowledge. The pipe system of aero-engine has following features:

Big quantity vs small space. The average number of the pipes in an aero-engine is 100 , 200 together with hundreds of pipe clamps; while the installation space for the multi-layer 3D pipe system is a 150 , 250mm thick cylindrical space between the engine jacket and the engine cabin.

Connecting multi-functional accessory system. The model aero-engine has more than 50 accessories with all kinds of functions and various outer shape and material. The pipe system has to connect all the accessories and transfer fuel, lubricant, coolant, and control signals.

Many constraints. The pipe system of aero-engine should meet the requirements of manufacturability, installation, maintenance and replacement, vibration and stiffness, thermal fatigue and distortion, and electrical limitations.

The proposed pipe routing algorithm is applied in an aero engine pipe system design problem to testify the effectiveness and efficiency of the algorithm.

5.2 Structure of design and simulation platform

The platform is mainly made up of two modules, the pipe design module and the pipe simulation module. Figure 5.1 presents an overall structure of the whole system.

The design module is responsible for reorganization of geometric information of the aero-engine 3D UG model, accessories and starting and ending points of pipes. In the UG pipe laying plug-in mode, based on diameter and timber of every pipe, liquid in pipe, velocity of flow and life of pipe, the module can automatically recognize the dense and sparse sections, planning proper sequence of pipe-laying. Besides, the path of every pipe is also generated by using the shortest path principle or quadrature rules without breaking laws of design of pipes and design process.

The pipe simulation module transfers geometric data of the 3D UG models of pipes to simulation system of aero engine pipe through interface with 3D UG model, fluid structure interaction, strength, vibration and life to generate files concerning adjustment about pipe-routing which can be turned back into pipe design module to further remedy the path of pipes in the aero engine pipe system simulation platform. Every big module consists of several small parts, figure 5.1. gives an complete structure of the platform and information flow.

5.3 Pipe design module

Both the above visible graph method and 3D pipe-routing algorithm are realized by pipe design module.

5.3.1 3D UG Model

Aero-engine 3D UG model is a present universal 3D model including geometric and processing parameters of aero-engine and corresponding accessories generalized by UNIGRAPHHICS 3D mechanical design software. This software contains all the mechanical parts design information except from pipes and is a useful guide model for design of aero-engine and later period of production, as figure 5.1 shows.

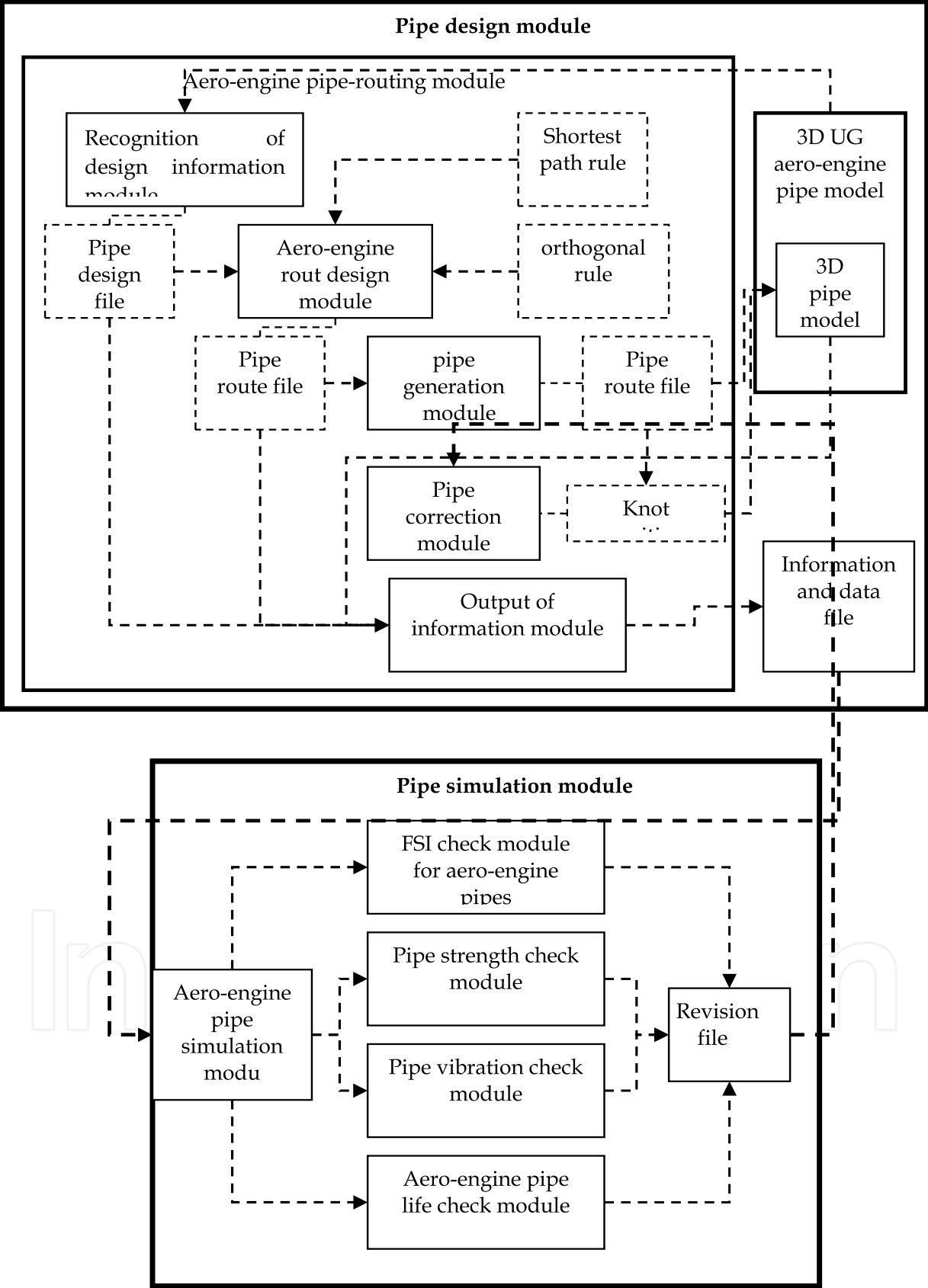


Fig. 5.1. Design & simulation platform structure for aero-engine pipe system

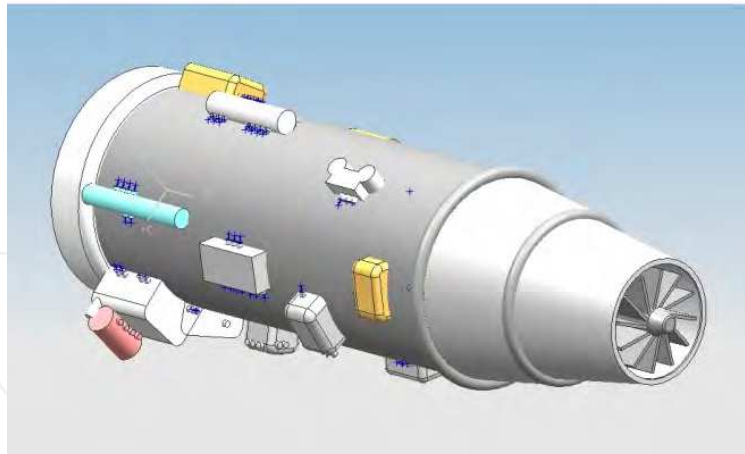


Fig. 5.2. 3D UG model of aero-engine

5.3.2 UG pipe-laying plug-in model

UG pipe-laying plug-in model is an OPEN API or OPEN GRIP interface using C language or GRIP language for programming in UG which is made up of recognition of aero-engine design information module, pipe-routing module, pipe-generating module, pipe-correcting module and output of aero-engine information and processing parameters module.

Recognition of aero-engine design information module is responsible for reading and storing of the starting and ending information of pipes of aero-engine 3D UG model. This model can recognize hundreds of pipes with various information of starting and ending points and store it in a information file using a general format. As figure 5.3 shows, this module can use UG grip file sweep.grx to scan UG aero-engine casing model to generate unified aero-engine casing geometric information text file and transfer this information to MATLAB for later application by employing inputting file load_layer.m and transforming file base_data.m in MATLAB. The similar approach applies to pipe geometric information which enters MATLAB by transforming pipe_info.grx to pipe_info.txt and further obtaining load_pipe.m using pipe-inro.m.

The aero-engine pipe-routing module can accomplish pipe-routing based on the information of starting and ending points in recognition module and geometric data of aero-engine casing and accessories by using the 3D pipe-routing algorithm in section 4.

This module can allow choosing whether the principle of pipe-routing is the shortest pipe path principle or the traditional orthogonal rule. The shortest pipe path principle focuses attaining the shortest path while the orthogonal rule emphasizes to lay pipes according the engine casing's equidistant surface thereby ensure the beautiful orthogonal pipe routes. Here we use the shortest path rule to produce pipe-routing file. The detailed information flow can be seen figure 5.4. and the algorithms in all the parts can be referred to mathematical modeling and algorithms in section 4.

Aero-engine pipe generating module is based on the above recognition of aero-engine design information module and aero-engine pipe-routing module. On the one hand, it uses the information stored in these two modules to output pipe_route_final.txt by pipe output transform file, further produces the corresponding axis of pipes in aero-engine 3D UG

model by UG interface program centerline.grx and 3D model using tubing.grx; on the other hand it outputs pipe_route_final.frame file to simulation module. This module's final UG pipe models will decide the real pipe geometric and manufacturing information.

Aero-engine pipe correction module is for correcting the 3D models generated by aero-engine pipe generating module. This model can correct the nodes in centerline of pipes to change pipe routes by correcting pipe_route_final.m, it also can alter the diameters of pipes to change appearance of pipes, as figure 5.1 shows.

Output of aero-engine pipe information and process parameters module can output and store the final aero-engine design information and process parameters. This model uses TXT format to store and output all the aero-engine pipe 3D models' information of starting and ending points, diameters, paths (stored in nodes in centerlines). Any pipe's design information and process parameters can be searched by this txt, namely pipe data and process parameters file.

5.4 Pipe simulation module

The pipe simulation module is developed based on fluid structure interaction simulation analysis and strength, vibration, life detecting and simulating software. It achieves automatic transferring of various simulation data and integrates multiple databases, like database of pipe materials properties, database of fluid parameters and database of pipe parts (pipes, clamps, joints and other parts) finite element models. Thus it can fulfill the concurrence of simulation of solid structure interaction of pipe system [23-26], strength verifying, vibration check, and life adjustment.

Pipe detection module contains detection module of fluid structure interaction of pipe routes in aero-engine, module for strength verification, module for vibration check of aero-engine pipe system, module for life check of aero-engine pipe system. The following part will give a detailed account about detection module of fluid structure interaction.

5.4.1 Detection module of Fluid Structure Interaction (FSI)

5.4.1.1 Importance of FSI analysis

Static index needs to be considered in a pipe filled with fluid, besides as for pipe system requiring strict working conditions (aero-engine pipe system, nuclear reactor pipes) transient index also is needed. When velocity of fluid in pipe changes drastically, fluid structure interaction needs to be taken into account to verify pipes' safety accurately. The most common transient phenomenon in pipe is the water hammer phenomenon, a fluid impact effect caused by the sudden closure of valve. When it happens, the whole system is susceptible to movement due to its massive impact. At this time, we can't separate fluid from structure to build models, so FSI analysis is implemented instead [27].

5.4.1.2 FSI problem in pipe system of aero-engine

As for cases of unstable pipes, as figure 5.3 shows, the traditional water hammer effect analysis, a combination of elasticity and pressure wave, isn't applicable. When pressure wave in figure (a) passes the twist on the right, the difference of pressure in corners on both sides result in movement in figure (b). Due to this reason pressure in right corner decreases

while pressure in left corner increases. This movement causes transmitting of pressure wave in pipes, and in turn causes movement of pipes, repetition of which forms vibration [28].

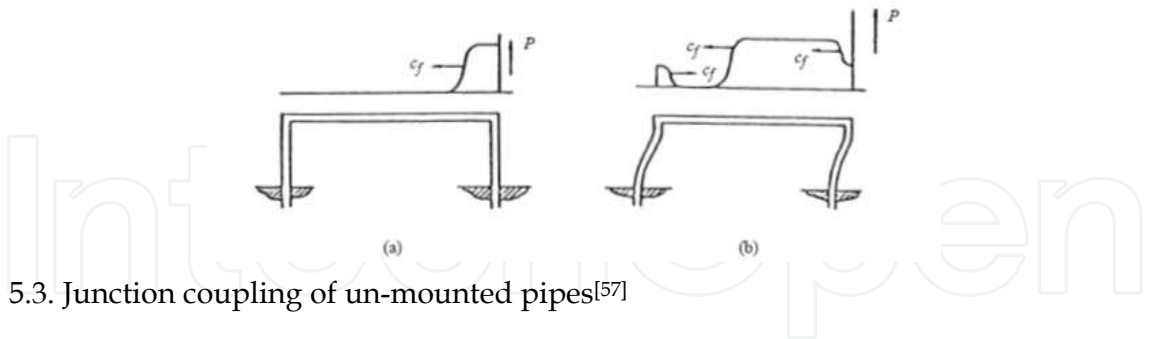


Fig. 5.3. Junction coupling of un-mounted pipes[57]

The above situation seldom happens in aero-engine pipes for pipes are usually fixed on jacket surface of aero-engine with clamps firmly. Of course FSI is possible if accidents occur to cause loose and failure of clamps, and the possibility of failure of pipes is also augmenting. Apart from this the following FSI situation is worth considering.

As figure 5.4 shows, fluid moves with velocity V in figure (a), reference pressure P at this time is 0; in figure (b), as fluid suddenly stops, the pressure is correspondingly rocketing quickly and pressure wave is transmitted with velocity c_f accompanying with expansion of pipe walls, as figure (c) shows. This kind of expansion spreads across the surface of pipe with velocity c_t and causes constriction of pipe walls in other places. This contraction generates a second increase of pressure spreading with velocity c_t (c_t is usually greater than c_f) which is often called precursor of wave, as figure (b) shows.

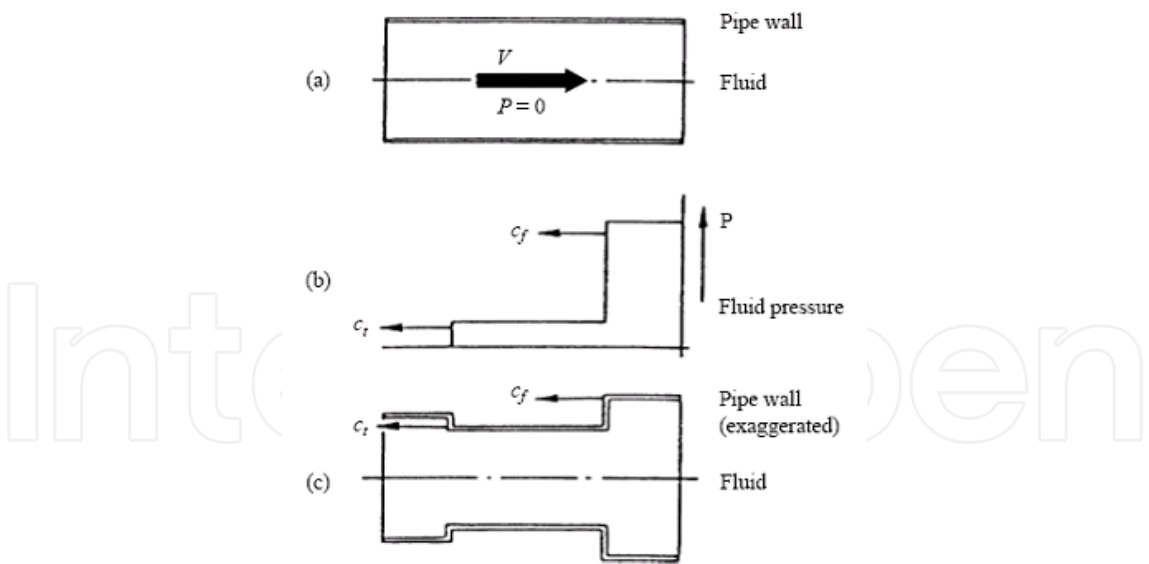


Fig. 5.4. Poisson coupling in normal case [57]

5.4.2 Feedback information of FSI analysis

Based on the FSI analysis, we can find working conditions need to be considered in design of pipes. Based on results of FSI analysis and the possible operations like operation of valves and sudden change of velocity of fluid and impact (lateral and axial impact) we can decide

whether straight pipe or elbow pipe is a proper solution. When faced up with frequent axial impact, it's more feasible to replace straight pipes with elbow pipes and to use more pipe supports; while there are more lateral impacts, results of FSI analysis should be taken care of to meet working needs of pipes and increasing use of pipes according to specific conditions is reasonable.

What kind of pipe should be used at the start and end point of pipe? How many clamps and what kind of clamps is proper? To solve these questions, we can't simply rely on vibration analysis and strength analysis, FSI analysis is indispensable to decide the suitable structure of pipes. If a straight pipe must be substituted by an elbow type based on FSI analysis, we can regard results of FSI analysis as human experience and knowledge which can be transformed to a virtual obstacle between two endpoints of the pipe added to unfeasible workspace. Thus based on the pipe-routing algorithm in section 4, it's natural to obtain an alternative strategy, namely the replacement of straight pipes with elbow pipes to preclude failure of pipes in FSI analysis.

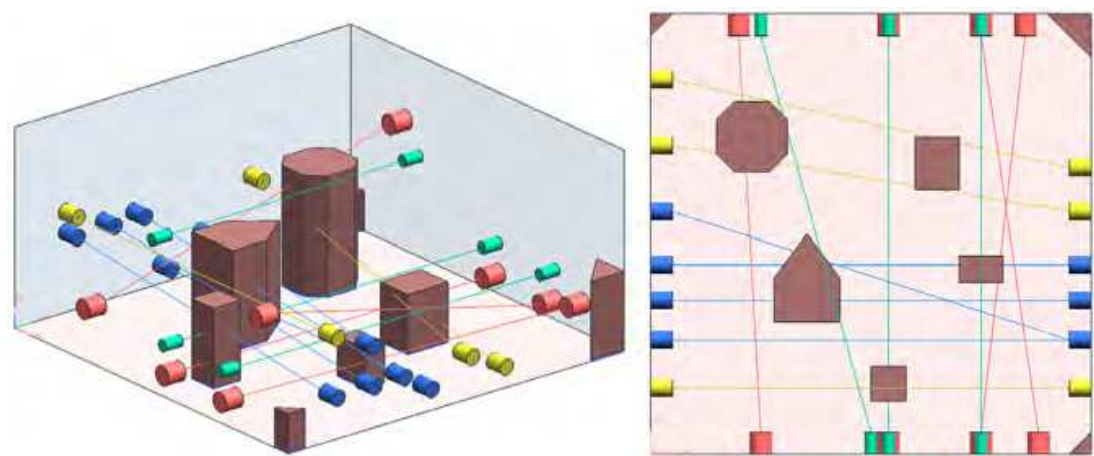


Fig. 5.5. Pipe route configuration based on FSI analysis

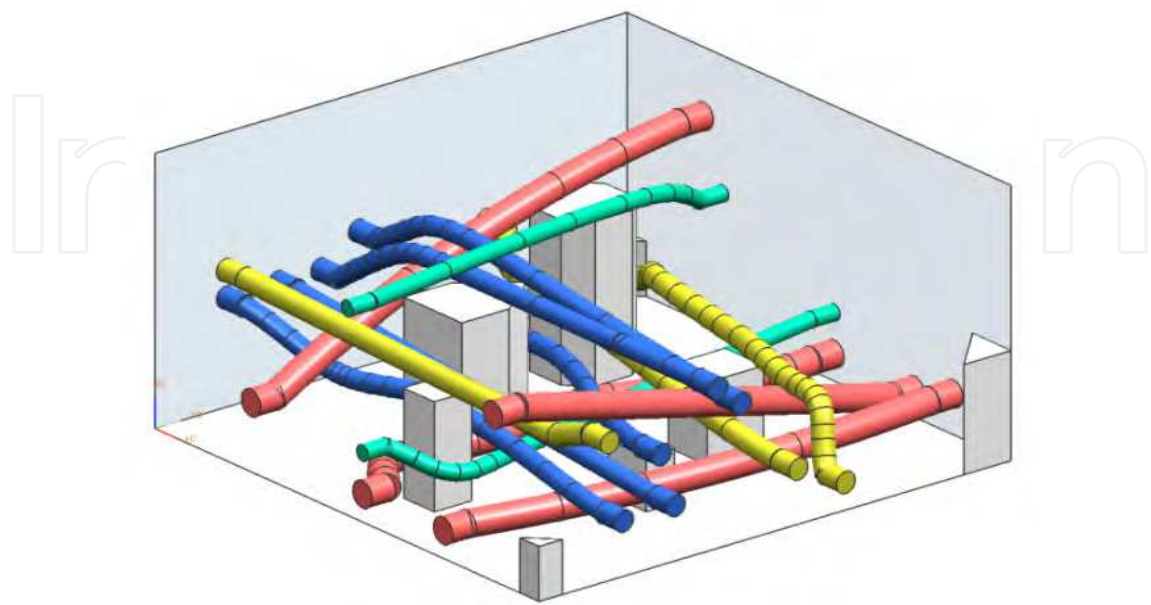


Fig. 5.6. Pipe routing results after FSI analysis

As figure 5.5 shows, the blue circles signify start and end points of pipe. This pipe is initially supposed to be straight, however based on FSI analysis, this pipe can't withstand massive axial impact, it needs to be replaced by an elbow pipe and a support needs to be added in the bending section. So an obstacle symbolized by a red circle can be added to force generation of elbow pipe to meet results of FSI analysis. The ultimate result of pipe-routing can be seen in figure 5.6 with arrow denoting the effect after modification.

From the above successful application of FSI analysis results in optimization of pipe-routing, we can find FSI results, based on knowledge and logical deduction which are accentuated by symbolism, can be finally employed in solving problems by make virtual imaginal changes integrating mathematical deduction and knowledge of the predesigned solution. So this application illustrates our former conclusion that logical thinking is a special type of imaginal thinking.

5.5 Simulation results

The aero-engine mechanical model is set up in UG NX4, by using self-developed interface, the geometry data of the aero-engine and pipe starts, ends and diameter information are transferred into MATLAB database as input of calculation. The algorithm is written with MATLAB language and the calculated pipe route result is feed back to UG module to generate 3D pipe modules^[29-31].

5.5.1 pipe-routing without obstacles

As shown in Figure 5.7, the algorithm is applied to a non-obstacle aero-engine model.

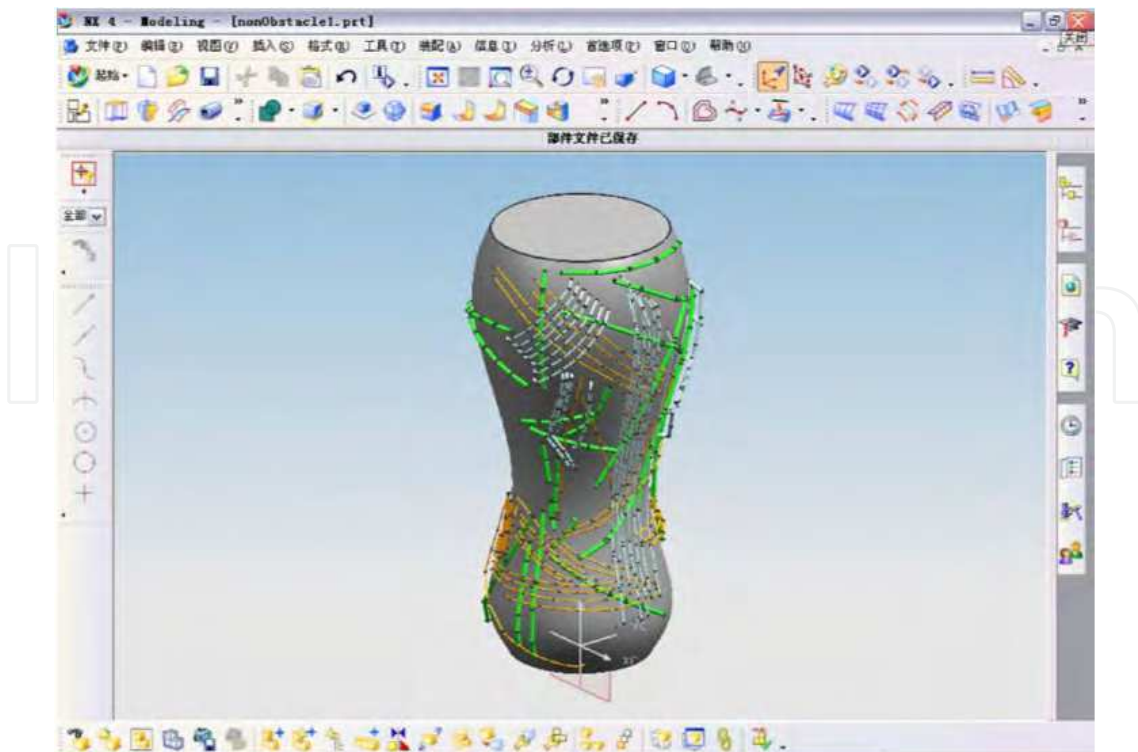


Fig. 5.7. Non-obstacle pipe routing

The aero-engine model is a revolved body with no accessories, the length (Z-direction, namely the air flow direction) is 5,000 mm, the diameter of the body is from 1,520 to 2,400mm; the free space gap of the aero-engine is no bigger than 150mm (from the outer surface according to the engine to the installation cabin inner surface). 67 pipes of functions as lubrication, cooling, information transmission, fuel, etc. are divided into three layers, from inside to outside displayed with different colors (green, orange, and white).

5.5.2 Pipe-routing with obstacles

As shown in Figure 5.8 and 5.9, the algorithm is applied to an aero-engine with all kinds of shapes of equipments.

The aero-engine model is very much similar to the real situation (real engine model is not allowed to display according to local government regulations), the length (Z-direction, namely the air flow direction) is 3,000mm, the diameter of the engine jacket is from 250 to 1,290 mm, six accessories of simplified shapes are included, the free space gap between the engine jacket and the installation cabin is no bigger than 150mm. 86 pipes of functions as lubrication, cooling, information transmission, fuel, etc. 86 pipes are assigned into five layers, from inside to outside displayed with different colors (yellow, green, blue, white, and red).

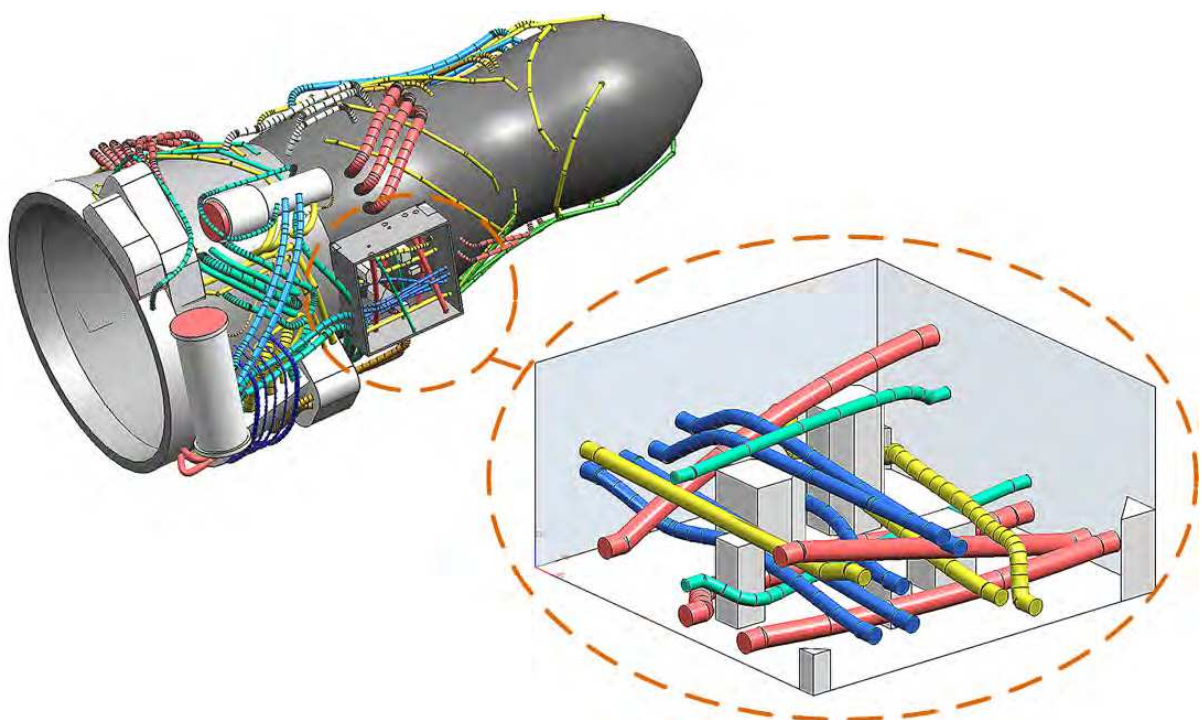


Fig. 5.8. Simulation of pipe routes planning for an aero-engine model

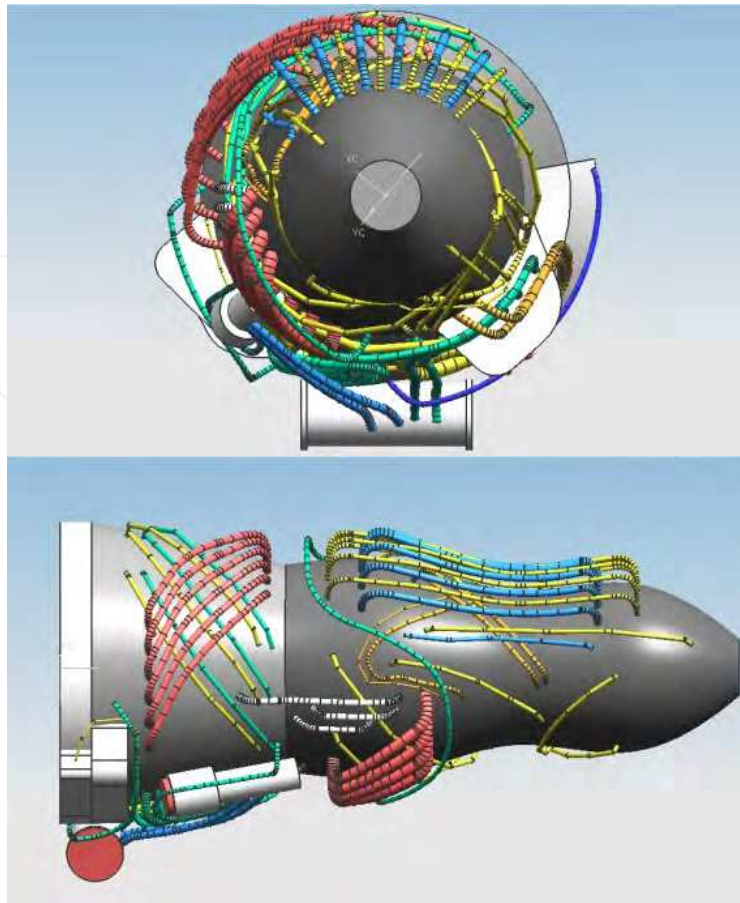


Fig. 5.9. Simulation of pipe routes planning for an aero-engine model (back & front view)

6. Epilogue

There exist serious conflicts between different schools of human thinking style. Meantime many engineering problems still heavily rely on human knowledge and experience for instruction so imitation of human thinking is a valuable and urgent job. Because information transmitted by the whole human thinking and the expression of it are both based on high dimension neural images which can be perceived and imagined, so we hope by imitating human thinking, we can find a way to solve engineering problems.

Autonomous pipe-routing system problem like aero-engine with hundreds of pipes within a limited gap, extraordinarily depends on human experience, is hard to solve by traditional AI frame. This article discussed a new kind of fundamental thinking style: imaginal thinking by forming images and comparing them holistically and directly. Moreover, we imitate human imaginal thinking to develop a novel pipe-routing design methodology, which combines the accurate massive computational capability of computer with the pipe-routing experiences or knowledge of skillful human.

By imitating human's imaginal thinking and using the graphs as information media, a novel pipe assembly planning algorithm has been introduced. Different from other computer logic algorithms, the human's imaginal thinking algorithm quantifies the skillful technicians' experience and intuitions while planning pipe routes. Comparing with other algorithms,

this algorithm takes all kinds of pipe routing constraints into account and automatically conceives pipe routes with simpler computational complexity which is more effective and efficient. For a certain pipe routing problem, the algorithm can sort the pipes with order chosen rules and translate the obstacles and constraints into pipe routing map (the inaccessible area distribution), subsequently, the output pipe routes are very much alike human brain's work. The results of the article are generally applicable to all kinds of routing problems, and thus have a wide range of applications, such as robot collision-free path planning, PCB design, process plant layout planning, ship pipe system design, and aero-engine pipe routing. Particularly, it is used in this chapter to design an aero-engine pipe line system. On this basis, two results for non-obstacle pipe routing and obstacle pipe routing are presented. During the actual design of aero-engine pipes, tons of information concerning various areas like mathematical models, routing algorithms, static and mobile strength, fluid, vibration noise and FSI interaction is needed. The frequent interaction and transfer of information call for a common simulation platform to manage design tools, design process, data of simulation and simulation process. Thereby we put up a platform suitable for design of aero-engine pipes and simulation process. Correlations between former algorithms and modules of platform are explicated. Besides, another crucial question in pipe-routing, FSI problem is accentuated and pipe-route method based on FSI analysis is presented. The simulation based case studies demonstrated the effectiveness and high efficiency of our pipe-routing design method and led us to a better understanding of some of the essence of human thinking.

Our future work is to build a complete AI frame of imaginal thinking, on the basis of the effective and efficient pipe-routing system integrating vibration analysis and fluid – structure interaction (FSI) examination as the knowledge and experience for aero-engine will be extended to application in aero-engine assembly. We believe, with combination of human imaginal thinking style and machine computation capability, computers may finally have higher intelligence than humans in solving some complicated engineering problem like aero-engine assembly.

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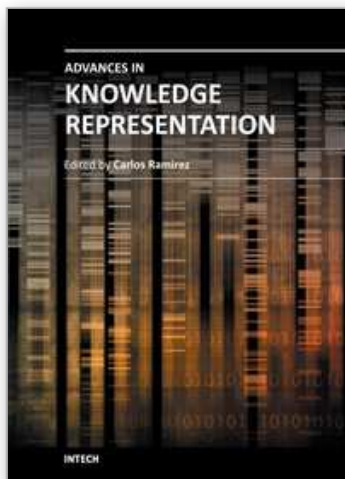
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