Workability and Mobility of Construction Machinery: Systematic Approach to Engineering Matters

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ABSTRACT

A new computerization technology is proposed and described in the field of **construction machinery**. As for social requirements, the need for prompt feedback about actual or potential performance deviation on job sites is growing because the margins of profit are getting smaller, and industry needs to be competitive. The history of the industrial automation has deeply related to the world economy so far. The design system (CAD), the production processing system (CAM) and the industrial robotics which has been developed afterwards in the 1960s, have greatly contributed to productivity improvement. Recently multi-copters (drone: small flying robot) are being developed already at some construction sites. Robotics has four major functions; A) operation (manipulation, hand and thumb, teach to art), B) movement (locomotion, foot, drive to run), C) sight (observation, eyes, sense to view), D) intelligence (artificial intelligence, brain, think to act). As for the construction machinery, A and B mentioned above deeply participate to their functions, together with C and D. Each function of A and B is related to robotics and mobility, linked together hand work and foot work.

Systematic approach to engineering matters is described as a thinking process to analysing and organizing engineering system. In the long history of human activity, culture, tradition, customs, life style, language have been formed gradually based upon politics, economics, natural and social environments. Experienced theory and praxis of human activity are evaluated from different angles in the field of design and construction works. Workability and mobility of robots are similar to human and animal acts. When looking at human growth and history of evolution, the tools and parts of machinery are deeply associated with human workability/mobility (sitting/standing, working/walking, handwork/footwork).The man-made systems are sometimes unstable and fragile against natural hazard and human errors. Their originality bases on nature's laws and rules. Risk management of engineering matters is associated with those nature's laws, rules and finally ISO standards.

Positioning and mobility is described by displacement (distance), velocity (speed) and acceleration (force) which are generating trajectory of movement. It is newly suggested that the trajectory is controlled by speed ratio of steering and driving successively and continuously instead of positioning by numerical data. **Speed and Trajectory Control (STC) method** is newly proposed, which contributes to remarkable reduction of controlling data and to easy modification of plan data on line at site. Induction method has less quantity of updated data than deduction method, and there are various kinds of advantages. The updated processing by GPS and laser beam instruments makes it possible.

The STC method bases on induction, updating planed data by observation in dynamics. Some application examples of the STC method explain their acts and validity.

Keywords : ***construction machinery, computerization technology, robotics, nature's laws, workability and mobility, risk management, Speed and Trajectory Control (STC) method, bulldozer, inertial land navigation, human activity, theory and practice***

1. Construction machinery and Robotics

1-1 Machine tools

Manipulator consists of several joints and links in the form of robot arms and hands. Their position and orientation are described in task-oriented space at work frame. Their mechanics are controlled mainly by two types; A) orthogonality type robot (having several prismatic and revolute joints), B) SCARA robot(having vertical prismatic joints and two more revolute joints around horizontal axis). Multi-articulated robot behaves and works with more flexibility and complexity. Motion is controlled by automated mechanics with help of measure and survey instruments.

1-2 Construction machinery

They have two kinds of functions; A) work operation by machine tools, B) mobility by vehicle. The machine tools are mainly controlled by orthogonality type with simple but strong mechanics. The works are done as following; A) positioning (GPS in the universal coordinate system), B) movement to goal, C) operation by machine tools. The total station is required to link tool operation and vehicle movement.

1-2 Social requirements

The need for prompt feedback about actual or potential performance deviation on job sites is growing because the margins of profit are getting smaller, and the industry needs to be more competitive.
1) Productivity improvement by few members of people, because of labour shortage.
2) Computerization with ICT (information and communication technology) and skill (tact knowledge) transformed to standardization (explicit knowledge).
3) High quality work (precise construction works from cm to mm unit).
4) Work performance up (cost/price reduction, productivity improvement, shortening term of works).

1-4 Engineering requirements for construction machinery in the field of earth works

1) Bulldozer: Automation for blade control system is expected for earth working and grading.
2) Motor grader: The performance similar to bulldozer is required. The blade is hung in center among front and back wheels as a floating structure, which makes it flexible to irregularity of the road surface. The mechanism is also applicable to snow-plow at streets.
3) Asphalt finisher car: The expansible screed with heating device distributes asphalt chemical mixture uniform over the road surface and spreads it all equally. Major requirements are as follows; a) equalizing thickness uniform, b) minimizing asphalt volume less, c) finishing surface flat .
The blade divided in two pieces (so called, iron) is provided to grade the finishing surface uniform along the cross profiles of the road.
4) The shovel car is used for crushing the old pavement, then loading it into the dump tracks. The mechanism is illustrated in **Fig-2**. An arm and a bucket of the shovel car become a target of the automation by means of manipulation.
5） An interlocking movement of manipulation and locomotion are important to automation of construction machinery. The power and delicacy are required at the same time. Brain and eyes make interlocking combination of footwork and handwork.

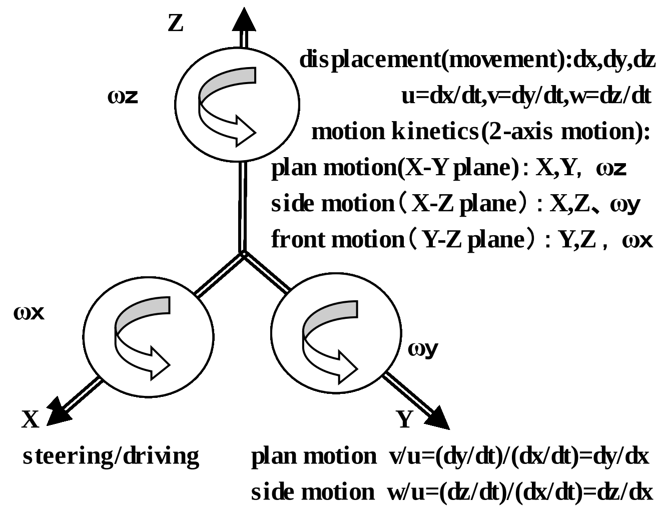
1-5 Autonomous aerial robots to monitor construction: drone, UAV

Multi-copter (Quadcopters, Hexa-copters), small aerial robots (drones: a self-guiding small flying robot) with four or six propellers ranging in size 30~120cm across and also known as Unmanned Aerial Vehicles (UAV),are being developed already at some construction sites. But their use is currently limited to taking photographs and videos with GPS.
The computer-controlled aerial robots automatically navigate the job site indoors and outdoors, conduct visual inspection with on-board cameras,etc. The robots measure construction progress and provide detailed and continuous performance data on workers and equipment. The autonomous nature of the system in terms of data collection and the automated performance analysis will significantly improve monitoring and control practices in construction.

2. Basic mechanism of manipulation and locomotion

2-1 Mobility and degree of freedom: mechanism of mobility, vehicle, steering/driving

Kinematics deals with location, velocity, acceleration, their derivatives and geometric properties in term of time. Flexibility of motion depends on degree of freedom which is associated with joint links. Position and orientation are described by numerical data mathematically at local frame in the specified coordinate system. **Fig-1** illustrates driving and steering mechanism of mobility for each vehicle. Motion kinematics are defined by Cartesian (X,Y,Z) coordinate and their angle axis. They are classified by plan, side, front motions with combinations of going straight (driving) and rotary (steering) mobility.



vehicle	motion	mobility	steering/driving
(drafter)	Y/X moving	X-Y plotting	
		shortest pass	dy/dx
car,bicycle	X : forward+(backward)	navigation	
	ωz:handle	turning	dy/dx
ship	X : forward+backward	navigation	
	ωz: rudder	turning	dy/dx
aeroplane	X : forward	navigation	
	ωy,ωz:rudder ,steering	rise+drop, turning	dy/dx,dz/dx
submarine	X : forward+backward	navigation	
	ωy,ωz:rudder,steering	submerge+float,turning	dy/dx,dz/dx
shovel car	X : forward+backward	promotion	
	ωy,ωz : arm+bucket	druging+loading,turning	dy/dx,dz/dx
bulldozer	X : forward+backward	promotion	
	Z: blade(updown)	druging+grading, turning	dy/dx,dz/dx

Fig-1 Mechanism of mobility: vehicle, motion, steering / driving

Table-1 Robotics and technology: functions and definition

physics	function	task	work frame,coordinate	technology
foot	drive to run (foot work)	locomotion,running driving by pedal	station frame,observation frame universe coordinate system	mobility power
hand	teach to art (hand work)	manipuration,work steering by handle arm tool	operation frame,task frame base frame wrist frame tool frame	robotics electronics kinetics mechanics
eyes	sense to view	target,approaching	observation frame,target frame	sensing, GPS
brain	think to act	position, orientation statics and dynamics	work frame,task frame, station frame,observation frame	synthesis cybernetics

2-2 Robotics and technology: functions and definition (Table-1)

Robotics has four major mechanics: A) vehicle(foot, drive to run) ,B) tool(hand、 teach to art), C) goal(eyes, sense to view), D) work(brain, think to act). Each mechanics is associated with a variety of technology shown in **Table-1**. Position and orientation of tools are described at joint space, and then converted into Cartesian task space by mapping.

Multi-articulated robot behaves with more flexibility and complexity. The motion is controlled by automated mechanics with help of measure and survey instruments.

3. Systematic Approach to Engineering Matters

3-1 Growth and evolution: workability/mobility, shovel car, elephant nose, human arm offset

1) Among a variety of construction machinery, shovel car is most used in the construction sites.

2) Mechanics is consisted of A) locomotion for movement (foot work), B) manipulation for operation (hand work).

3) The shovel car (**Fig-2**) has orthogonality type mechanics with several prismatic and revolute joints.

4)Arm offset fe, fh: On standing, the offset below elephant nose (fe) and man arm(fh) are commonly arranged in constant, regardless of their big or small skeletons. A species has common offset for walking and working.

5) The shovel car has ideal position fs for convenience of working and running, similar to elephant.

6) Human arm offset (fh): fh(man)=62~63cm,fh(woman)=52~53cm

The common property has a great influence on life style. It unifies standard of furniture (height of desk and chair)and sport goods(length of golf club, strike zone of baseball). When looking at human growth and history of evolution, arm offset fh is deeply associated with their workability/mobility.

7) Arm offset fh changes in growing process from child to adult. When arm offset fh reaches to 62~63cm, a man is authorized to be an adult. The height of desk and chair at elementally school rise up progressively as they grow up to the upper grades from the lower grades step by step.

8) In case of bisexuality problems, we may distinguish sex by arm offset which nature he or she belongs to.

9) In the long history of human evolution, workability/mobility (sitting/standing, working/walking, hand work/foot work, indoor life/outdoor life) has been changing gradually by natural and social circumstances, and may has had some influence to human arm offset.

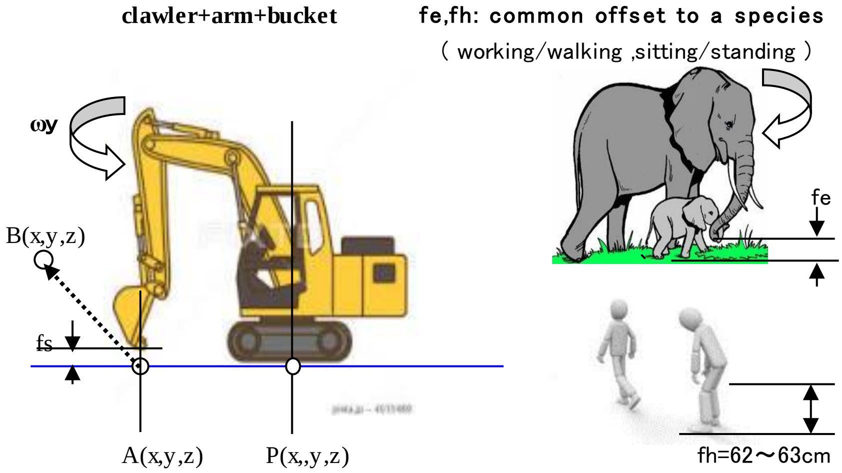


Fig-2 Workability/mobility: shovel car, elephant nose, human arm offset

3-2 Nature and arts: giraffe / Tokyo Sky Tree, risk management, growth/evolution

Similarity at the tallest system

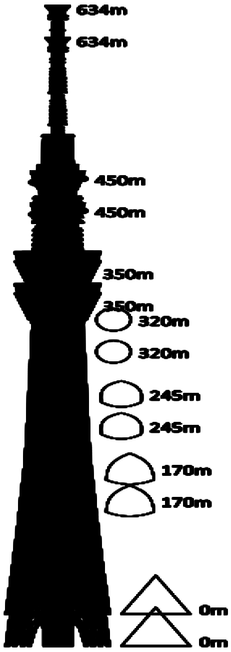
Fig-3 illustrates similarity of a giraffe and the Tokyo Sky Tree tower. Their workability is being developed for the wide views and better performance (wide access/communication) in the process of growth and evolution through struggle for existence.

Risk against hazard (alien): animal (4 legs) /tripod (3 legs) system

The Tokyo Sky Tree stands on the tripod basements. When the tripod tower is subjected to an earthquake, three legs resist against overturning due to horizontal forces. The dynamic model bases on interaction between two legs versus one leg where compression and tension forces is generated alternately. According to the brief estimate (**Fig-3**), in case of the tripod, maximum compression and tension forces for each leg are remarkably larger than the behaviours in case of four legs. The tripod structure is unstable and fragile definitely.

Risk management: regional disasters, risk control, risk diagram, nature laws

1) Risk is defined as disaster damage (X) times its occurrence probability(Y) based upon the Pareto distribution curves of probability density function **(Fig-4, Fig-5).** A shape parameter k characterizes shape/concentration and cause/effects of the system.
2) The Pareto distribution bases on nature's laws and **Table-2** is available in many fields of human activity (population), economy (wealth, inequality, globalization), and natural hazards (EQ).
3) Risk boundary (X*Y=c, k=1) implies potential energy of the system and toughness against disasters, and expresses rating scale to risk against hazards.
4) If risk zone is below the risk boundary, the system is safe, if over, the system is dangerous and then should be revised and modified for safety.
5) The risk boundary is specified by authorities with codes though public acceptance.
6) Risk diagram is classified in four categories(A, B, C, D) depending on scale of damage*occurrence (**Fig-4**). Risk control methods are as follows; a) Risk built-in(maintenance free, no care), b) Risk reduction(strengthened, protected against failures), c) Risk avoidance(original plan is rejected and eliminated), d) Risk transfer(guaranteed and covered by insurance).
7) Regional disasters and risk control; In serious cases, prevention and protection are considered. In mild cases, mitigation program is planned by reductions and distribution of the effect.
8) An animal with three legs never exists in nature. The tripod structure loses toughness against hazards and it is sophisticated arts, not in a natural, pure, or original state against nature's law. Big system means big disaster once contingency occurs in reality by natural hazards and human errors.



Risk management: Stability against EQ

P1=aW/10 a=0.4g,H1=570m,H2=170m

H1 Overturning moment due to EQ

Mt=P1*H1+P2*H2

Mt=(170*0.36+570*0.04)W=84W

vertical loads due to dead loads

W/3 (3legs), W/4 (4legs)

In case of 3legs (risky)

V=W/3±Mt/B (each leg)

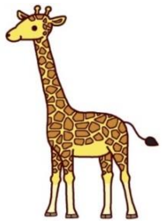
V=(1/3±84/B)W =(-0.87～1.53)W

H2 In case of 4legs (stable)

V=W/4±Mt/2B (each leg)

V=W(1/4±84/2B)=(-0.35～0.85)W

P2=9aW/10



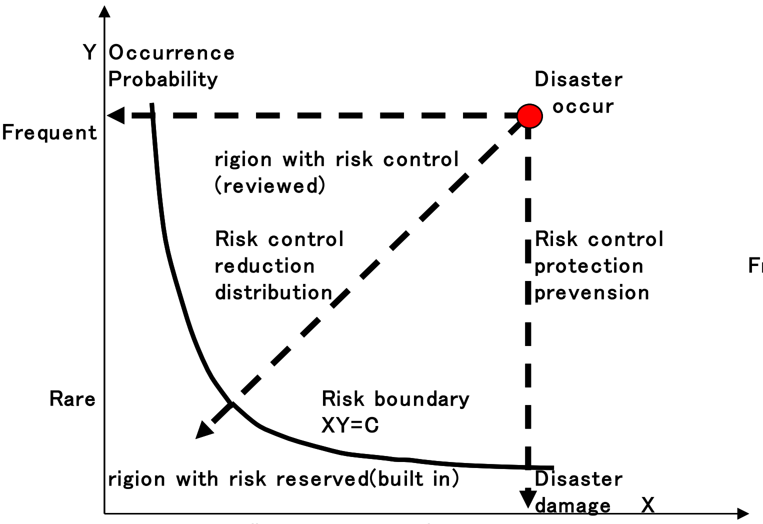
Giraffe
tall neck

Tokyo Skytree W=41,000tf、H=634m,B=70m

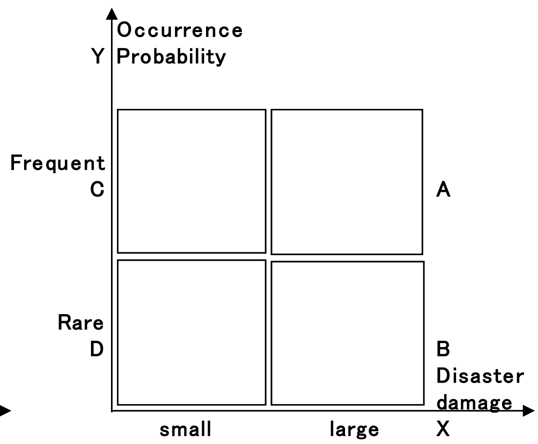
for wide view + wide commnication

for wide view + wide food access

Fig-3 Nature and arts: giraffe and Tokyo Sky Tree



Risk Diagram (Occurrence probabity-Disaster damage)



Risk category

Category	Hazards	Risk management and control
A	Earthquake	1) large damage*frequent occurrence probability 2) high priority of risk controls against severe damage
B	Fire	1) large damage*rare occurrence probability 2)next priority of risk controls by risk transfer or risk built-in
C	Traffic	1) small damage*frequent occurrence probability 2) daily matters which often occurred without control
D	Work	1) small damage*rare occurrence probability 2) risk built-in with maintenance free

Fig-4 Risk management: risk diagram, risk category, risk matrix

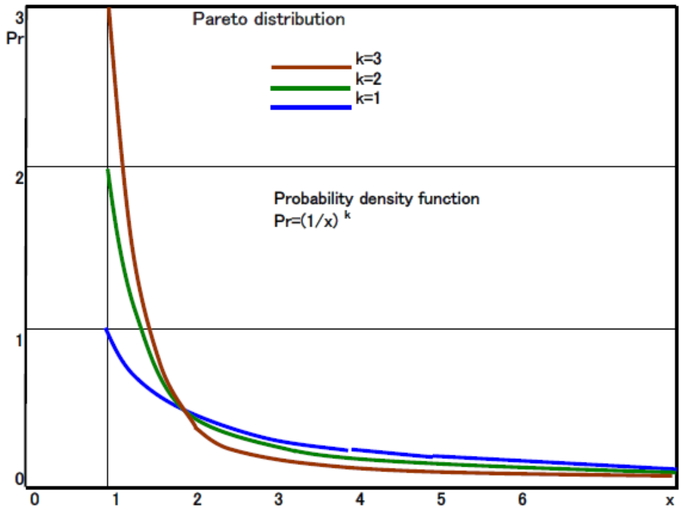


Fig-5 Pareto distribution, Pr= $(1/x)^k$
(probability density function)

Table-2 Pareto distribution: nature's laws, shape parameter k
(when k=1, it is in normal state, and equivalent to Zipf`s law)

Probability density function Pr=$(1/x)^k$ ∫ dx/x=log x, k: shape paremeter

k	status	distribution	shape	natural and social environments
k>1	too active	top heavy	sharp &concentration	barrier free, non-constraints, exess competition
k=1	stable	natural	shape of natural logarithm	nature, liberty / equality under justice, fare trade
k<1	reserved	long tail	flat& plain(closed society)	human inactivity, constraints, under development

	Tokyo Sky Tree	Tokyo tower	West Tokyo sky tower	SUM
height(m) practice	634	333	195	1162
rank N	1	2	3	
Ziph's law 1/N	(1/1)	(1/2)	(1/3)	1.833
height(m) theory	634	317	211	1162
construction year	2012	1958	1989	

Tokyo Sky Tree　　Tokyo Tower　　West Tokyo Sky Tower

Fig-6 The tallest towers in Tokyo: height and nature law, facts/Zipf's law

The tallest tower history in Tokyo: growth/evolution, practice/Zipf'law, science/engineering

A formula of Zipf's law by Zeta distribution is given by;

$F(m,s,n)=(1/m^s)/\Sigma(1/n^s)$ n=1,2,3, N

When s=1 , $F(m,N)=(1/m)/\Sigma(1/n)=1/(m*SUM)$

$SUM=\Sigma(1/n)$,N is total number of sampling data.

Pareto distribution coincides with social, scientific, geophysical, actual and observable phenomena. When shape parameter k=1, Pareto distribution is given as the same equation of Zipf's law. Pareto distribution is a continuous probability function. Zipf's law sometimes called the zeta distribution will be thought of as a discrete counterpart of the Pareto distribution. Fig-6 shows the top 3 tallest towers in Tokyo during the last half century. It takes about a half century to jump up to be as much as twice in the process of growth and evolution. Top 3 summation of height (1162m) is exactly the same SUM (1162m) due to Zipf'law accidentally. It is very interesting cause/effect problems to think why and how engineering progress matches nature's laws with human activity. Science is always permanent and universal whereas engineering is not infinite and local. Intellectual property is a work conceived from human wisdom created and invented valuably and usefully in economic benefits in social development. As shown in Table-2, natural and social environments in Tokyo are stable (k=1). There exists freedom in Tokyo sky. Japanese industry, civil engineering and architecture are in normal state and healthy. Correct systematic approach to engineering results in a part of science.

3-3 Deduction and induction: analysing/organizing, creation/improvement, ISO 9000 PDCA(Plan, Do, Check, Act)

Deduction goes forward to particular details from general principles and known facts. Induction comes backward to general principles from one's experience. **Fig-7** shows a pyramid type of work flow from design to construction.

Analysing/organizing: analysis/synthesis

Design work is analysing process based on idea, plan and concept, forming reverse pyramid shape in divergence mode. At the turning point where information reaches the maximum in quantity, the project switches to organizing process of construction work, building pyramid shape in convergence mode.

Deduction/induction: creation/improvement, theory/practice, ISO (PDCA)

a) Deduction (ISO Plan, Do) creates knowledge and experience through design and construction.

b) Induction (ISO Check, Act) improves the knowledge. Practice forms general principles from experience.

3-4 Information and communication: ICT risk, human errors, bias

The information is transmitted to other persons by communication. Human errors and bias occur at communication process, and information may not be transmitted correctly and definitely.

Human errors (matters of forensic engineering) : They result from the following defects .

a) Negligence: misunderstanding of design code and rules
b) Incompetence: incompetent, unqualified
c) Ignorance: imperfect design, lack of experience, no inspection
d) Misuse: out of design standards, miss-procurement, lack of maintenance
e) Disorganization: irresponsible system, lack of ethics, absence and delay, indifference
f) Miscommunication: deficiency of the organization system, bias

Bias (matters of risk management): It occurs mainly by media in particular among people. Bias is classified as follows.

a) normality bias, b) optimistic bias, c) catastrophe bias, d) expert bias, e) virgin bias.

In reality in Japan, nuclear contamination problems at Fukushima fall in difficulty of new construction and operation works in the nuclear power plants without public acceptance to the original plan. Bias makes crucial social impacts in the process of forming public acceptance.

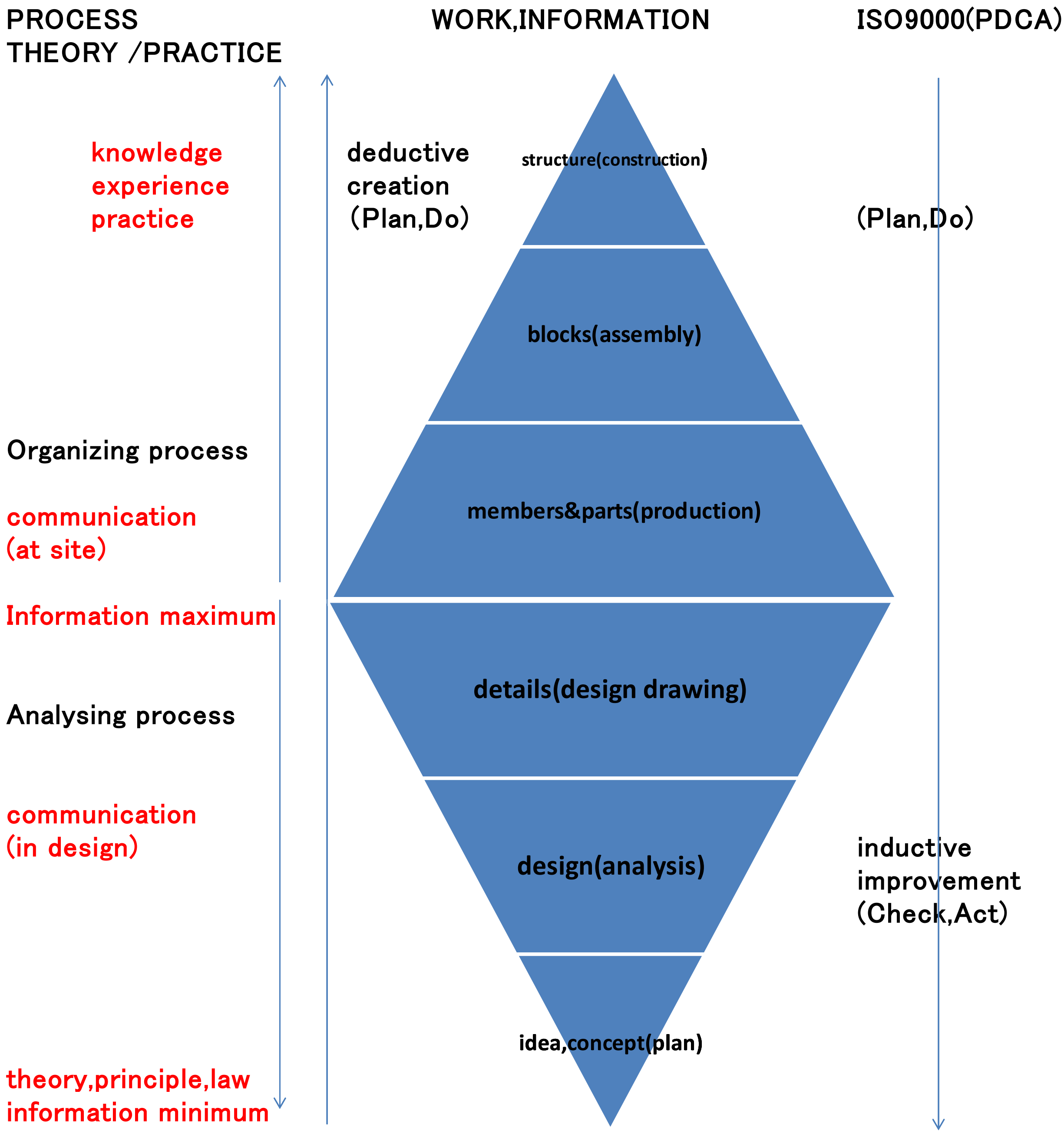


Fig-7 Systematic approach to creation and improvement
(analysing/organizing, theory/practice, design/construction, ISO9000 PDCA)

4. Trajectory and Shape: discipline, kinetics

4-1 Trajectory and Shape: nature laws

Webster`s Dictionary says that trajectory is the curve that a body (as a planet or comet in its orbit or rocket) describes in space. Trajectory is generated by nature`s law and descriptive science (mathematics).

Fig- 8 shows a ship trajectory (trail of the motor boat) and Mt.Fuji in Japan. When speed ratio of steering /driving is kept in constant, trajectory draws a spiral curve.The trajectory is consisted of consecutive splines. A spline connects two via points and is defined by mathematical function such as straight line, arc (circle), parabola, spiral and transition curves. The conic shape of Mt.Fuji is generated by volcanic flow/gravity. In nature, the conic involves conic section of circle, ellipse, parabola and hyperbola depending on an angle of projection surface.

Fig-8 Ship (motor boat) trajectory and shape of Mt.Fuji
spiral: Steering/driving conic: volcanic flow/gravity

4-2 Trajectory and Kinetics

Table-3 describes nature/arts, kinetics, trajectory, and discipline for each substance. Kinetics in space is mainly dominated by external force/gravity. The trajectory of the vehicle on land is determined by steering/driving and workability/mobility.

Table-3 Trajectory and kinetics: nature-mechanics-civil engineering, discipline

nature/arts	substance	kinetics(force/gravity)		trajectory	discipline
nature	planet	centrifugal force	gravity	orbit and focus(ellipse,parabola,hyperbola)	astoronomy
	Mt.Fuji	volcanic flow	gravity	conic	topography
mecha-nics	roket	space projection	gravity	projectile,high-arch trajectory and falling	ballistics*
	air plane	air float	gravity	planned trajectory control	aero mechanics
	submarine	sea float	gravity	float control by balloon and ballast	fluid mechanics
civil eng.	road	steering	driving	along generated trajectory of point array	road design spec
	bulldozer	blade motion	driving	costruction work for grading and levelling	blade control

5. Speed and Trajectory: STC method, principle, trajectory generation, usage

5-1 Speed and Trajectory Control method（STC method）

Principle: Velocity ratio v/u is proportional to gradient dy/dx.

Proof: **Fig-9** shows spline y=f(x), where via point (start) P1(x,y) moves to via point(goal) P4(x,y).

horizontal velocity $u=dx/dt$ ($dx=u\,dt$, $x=\Sigma dx=\Sigma udt$)

vertical velocity $v=dy/dt$ ($dy=v\,dt$, $y=\Sigma dy=\Sigma vdt$)

$$v/u=(dy/dt)/(dx/dt)=dy/dx \qquad \text{Eq (1)}$$

When v/u is kept in constant, moving distance x,y is proportional to each velocity u,v (x=ut,y=vt). The shape of Mt.Fuji seems to be conic **(Fig-8**). In this case, volcanic flow/gravity has generated slope dy/dx in form of circular cone. Similarly to air or sea inertial navigation system, the STC method makes car land navigation system possible along trajectory of lanes.

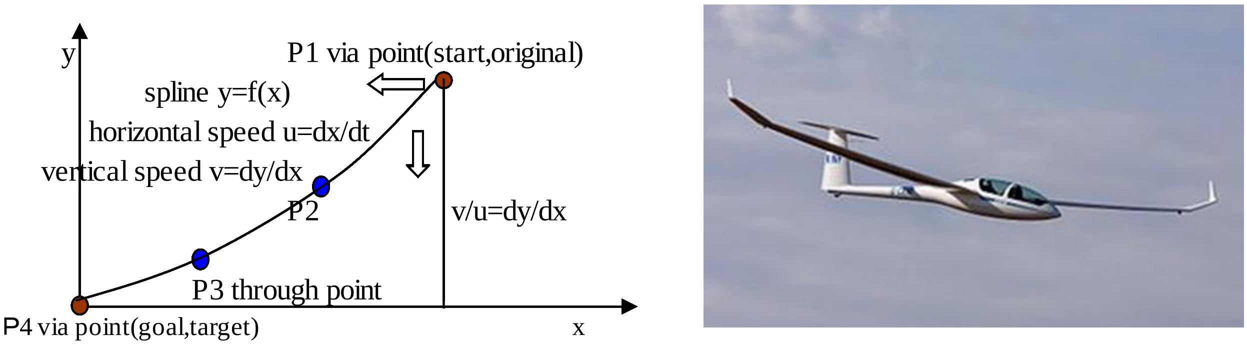


Fig-9 Trajectory: two-axis control, speed/slope, glider

5-2 Trajectory generation method by splines

Fig-10 shows trajectory generating methods by using various kinds of splines (functional curves interpolated). It illustrates v/u ratio to slope dy/dx. In usual, trajectory is given by via points or pass points array along plot curves sequentially and continually. In general, a spline is defined by various kinds of functional line segment.

1) Straight line: $Y=a+bX$

Two parameters are determined by two via points, to be shortest way to goal.

2) Quadratic curve : $Y=a+bX+cX^2$

Three parameters are determined by three via points in parabolic pass.

3) Cubic curve: $Y=a+bX+cX^2+dX^3$

Four parameters are determined by four via points or two pass points + two tangents. They are used where curvature changed. It includes one inflection point.

4) Spiral (clothoid) curve: It is used to gradually change curvature of road at transition zone.

5) Trajectory (point array curves interpolated);

It consists of many splines (straight line, circle, clothoid, as shown in **Fig-10**) which is generated to be smooth and continuous. For each spline, v/u is determined to be; 1) constant, 2) linear change, 3) non-linear change along pass.

spline	straight line (2 via points)	parabola (3 via points)	point array curves(multi-via points)
	Lx Ly	sag f L	
(x,y)	straight line	parabola	straight line, parabora,circle,clothoid
mechanism	the shortest pass with energy minimum	pass by projection/gravity	pass interpolated to be smooth and continuous
function	$y=(Ly/Lx)x=ax$ when Lx=0 (vertical), zero divide,unstable	$y=4fx(L-x)/L^2$ symmetry,equal distance to diredrix line and focus	$y=\Sigma f(x)=f1+f2+fn$ clothoid: curvature varies linealy with parameter A(steering / driving)
format	L1(Lx,Ly,line)	L2(f,L,parabola)	L3(R,circle),L4(A,clothoid)
slope	$dy/dx=Ly/Lx=a$	$dy/dx=4f(L-2x)/L^2$ x=0 : $dy/dx=4f/L$ x=L/2: $dy/dx=0$ x=L : $dy/dx=-4f/L$	$dy/dx=\Sigma df(x)/dx$
speed ratio	$v/u=dy/dx=a$	$v/u=4f(L-2x)/L^2$	$v/u=dy/dx$
spe. change	constant	linear change	non-linear change

Fig-10 Trajectory generation by spline functions

5-3 Smoothness and continuity of trajectory : observation data and spline joints (Fig-11)

Least squares method is used to define a spline by observation data at site. The constrained point is classified to be via point, others are pass points or though points.

A mathematical procedure for finding the best-fitting curve to a given set of points is used by minimizing the sum of the squares of the offsets ("the residuals") of the points from the curve. The sum of the squares of the offsets is used instead of the offset absolute values because this allows the residuals to be treated as a continuous differentiable quantity.
For smoothness and continuity of the trajectory, both ends of a spline should be tangent zero to turn into a straight line.

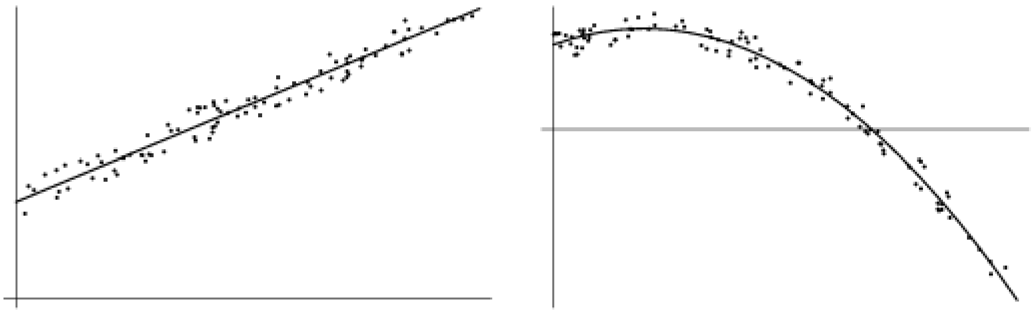


Fig-11 Least squares method and both joint ends (to be smooth and continuous)

5-4 Singularity problems: zero divide when u=0

In Cartesian coordinate frame, Eq (1) implies that singular point exists when u decreases to zero where v increases to infinite. The same phenomenon occurs when crossing the inflection points around at u=0. In reality, irregularity occurs to be unstable in the manipulation system. When an airplane speed slows down to zero by accident, it falls down to the earth, while the steering system v/u is not controlled. The trajectory of flight is out of bound. Singularity always exists theoretically whichever controlling methods are applied in the trajectory problems. Only way to be stable around singular zones is that the mobile mechanism of v is slowed down ,consequently kept or stopped in state of unchanging against divergence mode.

5-5 Usage of STC method: trajectory generating and tracing, inertial land navigation (Fig-12)

The STC method is available in two ways; A) Speed control v/u generates new trajectory dy/dx (new land construction), B) Car driving v/u traces existing trajectory dy/dx.
Highway lanes are specified in exact form geometrically by splines. It is possible to match car speed ratio of steering/driving(v/u) with road plane curves(dy/dx). By using GPS and lane sensing technology together, the STC method enables the automatic driving in the traffic lane (inertial navigation, unmanned aerial vehicle (UAV)).

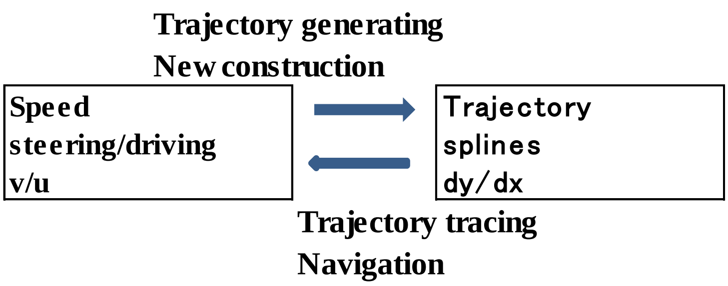


Fig-12 Usage of STC method: trajectory generating and tracing, UAV

5-6 Flight trajectory: inertial air navigation (Fig-13)

1) Assume that the flight trajectory is controlled to be parabola so that the touching angle at landing on point is normal to the ground.

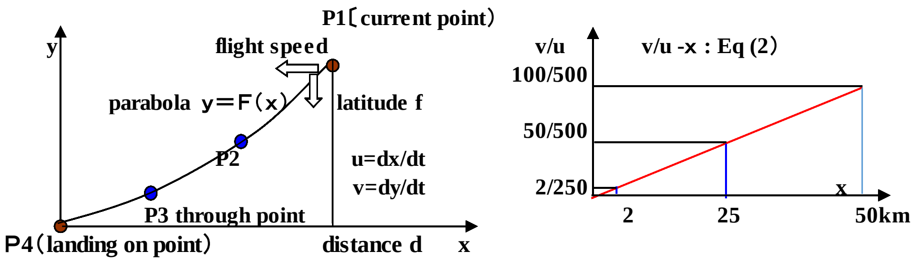
2) Parabola is defined to be a trace when throwing a stone in air under gravity. Its shape is determined by balance between horizontal force initiated by throwing and vertical force under gravity.
3) Fig.11 shows flight trajectory and v/u-x relation.
P1(x,y): a current position going forward , distance d=50km, latitude f=5km
P2(x,y), P3(x,y): through points during flight
P4(x,y): a goal point at landing on, d=0,f=0
4) Parabola equation: $y=ax^2$, a=5/50*50=1/500, dy/dx=2ax, down speed v, flight speed u

v/u=x/250 Eq (2)

5) Flight trajectory is demonstrated in **Fig-13.**
6) u/v-x relation: When an air plane is approaching toward the destination, speed ratio v/u is slowed down linearly and simultaneously according to EQ(2). It prevents sudden drop-rise, keeping planned trajectory.
7) For example, at position x=2km, y=16m; u=250km/h, v=2km/h
8) Down speed v is controlled by uplifting flap.

v=f(flight speed u, steering angle ω)

9) In general, flight trajectory is more complex depending on flight conditions.



Flight trajectory(x,y,u,v)

x(km)	y(m)	u(km/h)	v(km/h)
50	5000	500	100
25	1250	500	50
2	16	250	2

Fig-13 Flight trajectory: inertial air navigation

5-7 Road driving trajectory: at circular road crossing (roundabout, circle road) (Fig-14)
1) Circular road crossings sometimes have been planned and constructed for the major purpose of relaxing traffic jams due to speed down at crossing.
2) Corner points (**Fig.14**): There exists 32 points at conventional cross roads. Whereas, at roundabout it decreases to 8 points.
3) Driving trajectory:
Curve generation: trajectory f=f1+f2+f3+f4+f5(continuous curves with many through points). They are combined by straight line f1(inside or outside lane)+transition curve f2(cubic curve with one inflection point)+circle f3(transition curve) +transition curve f4(cubic curve with one inflection point)+straight line f5(exit lane)
4) Steering/driving(v/u) follows to the trajectory dy/dx.

u: driving speed by pedal

v: steering speed by handle

5) Configuration of circular crossing (radius R with cross sectional slope): Configuration is mainly determined by design speed of driving and number of traffic lanes. Curve transit v/u causes centrifugal force, and it specifies dy/dx of road alignment and crossing slope.
6) Circular intersection with less corners points and ETC(Electronic Toll Collection) system at toll gates make automatic car driving easy and rapid.

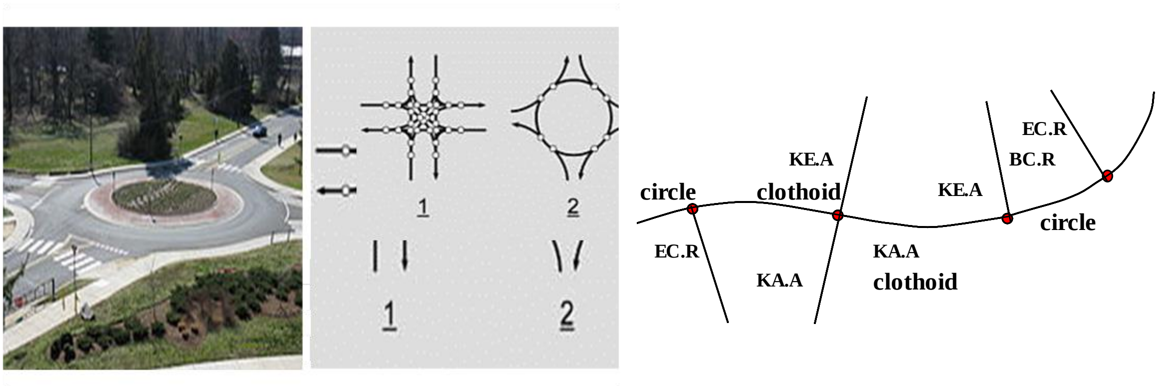


Fig-14 Driving trajectory: circular road crossing and road plan

6. Computerization of bulldozer: grading and levelling

6-1 Principle: application of STC method

Assume u= speed of crawler vehicle ,v= motion speed(up and down) of blade ,
dy/dx= trajectory(grading) slope.
Speed and trajectory control: v/u=dy/dx
Manipulation/locomotion: Civil work of excavation and grading ground is established by going along planned trajectory slope. Speed control v/u generates new trajectory dy/dx for new land construction.

6-2 Workability and mobility of bulldozer (Fig-15)

1) The crawler runs in movement space at observation (station) frame in the universe coordinate system. GPS and laser instrument watch its locomotion and position.
2) Blade works in task space at tool frame. Laser receiver knows its position (Z+ΔZ).
3) A bench mark point Q(X,Y,Z) is set up at station frame to be a base point for levelling at GL-0.
4) Locomotion movement of point P(X,Y,Z) follows Cartesian trajectory. According to positional information about the present position by GPS and laser, the planned position is updated.
5) The blade controller follows updated spline functions (**Fig-10**).
6) When stopping, the blade position is memorized, then, re-starting begins from there to goal.

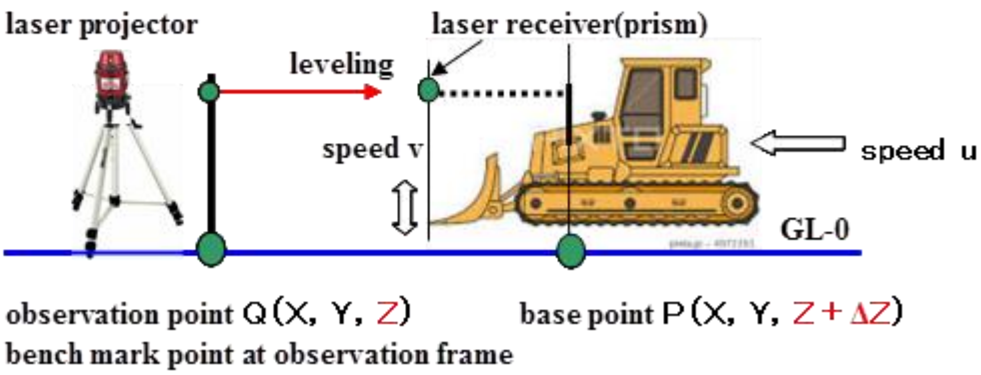


Fig- 15 Blade control system of bulldozer for grading

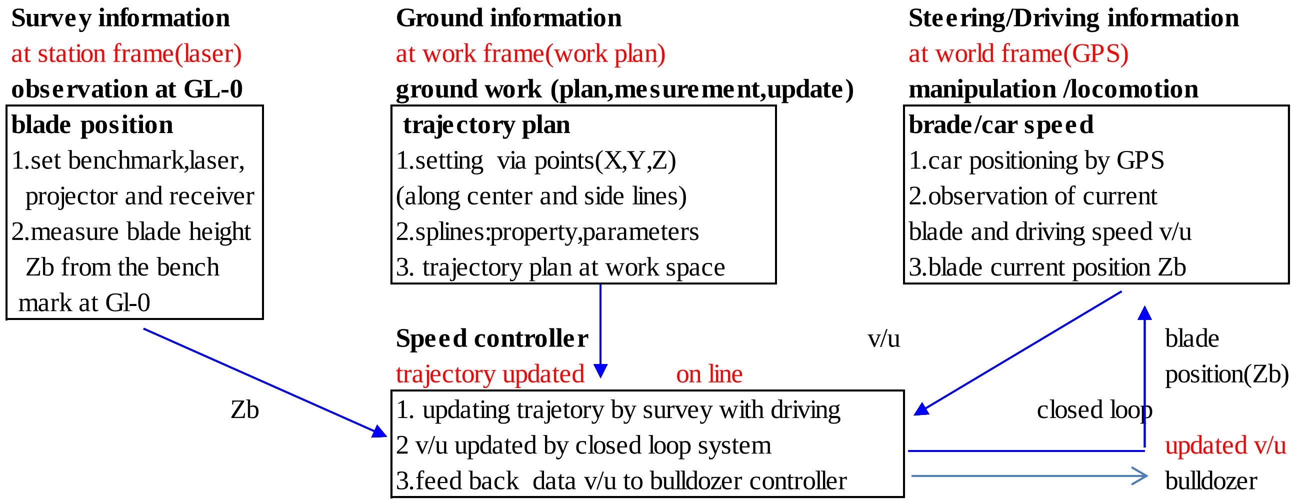


Fig-16 System flow of blade controller by STC method: set up to bulldozer

6-3 General use: pavement works, civil works, snow-plow and ground decontamination

1) General civil works: land excavation, ground grading and levelling.
2) Road pavement: road bed, road ground, pavement finishing
3) Large-scale parking lot: grading and levelling with gradual slope downward to drainage
4) Snow-plow at street: mainly by motor grader
5) Ground decontamination: strip off the lamina soil by motor grader or bulldozer.

6-4 Speed controller set up to bulldozer: mechanism of controller (Fig-16)

1) Major function: The speed ratio u/v is updated based on several information, A) planned data(trajectory, position ,spline with some parameters), B) Measured data(Crawler position P(X,Y,Z), speed ratio v/u, and blade position(Z+ΔZ)).
2) Correspondence: They are updated by some pass rate on line at real time, by means of closed loop methods.
3) Laser projector is set up at base point Q(X,Y,Z), while laser receiver is set up vertical at blade center linked to crawler, normal to the ground.
4) Working condition and situation on site: The land flatness is required to some extent, hopefully the gradient to be less than 2～3%. Crawler speed is required to be stable without sudden change.

CONCLUSION

Systematic approach to engineering matters

1. Workability and mobility of robot are similar to human and animal acts. An interlocking movement of manipulation and locomotion are important to automation of construction machinery.
2. Brain and eyes make interlocking combination of footwork and handwork.
3. When looking at human growth and history of evolution, tools and parts of machinery are deeply associated with human workability/mobility (sitting/standing, working/walking, handwork/footwork, indoor life/outdoor life).
4. Design work is analysing process based on idea, plan and concept, forming reverse pyramid shape in divergence mode. At the turning point where information reaches maximum in quantity, the project switches to organizing process, building pyramid shape in convergence mode.
5. Deduction creates knowledge and experience through design and construction works. Induction

improves the knowledge, then the practice forms general principle from experience.

6. The information is transmitted to other persons by communication. Human errors and bias occur in the communication process and may not be transmitted correctly and definitely.
7. The man-made systems are sometimes unstable and fragile against natural hazard and human errors. Their originality bases on nature's laws of science and rules. The risk management of engineering matters is associated with those nature's laws, rules and finally ISO standards.
8. Correct systematic approach to engineering results in a part of science.

STC method: advantages, productivity, workability/mobility, general use, UAV

Positioning and mobility is described by displacement (distance), velocity (speed) and acceleration (force) which are generating trajectory of movement. The STC method stands on a principle that steering/driving ratio (v/u) is proportional to trajectory gradient (dy/dx).

1. The STC method bases on trajectory definition and generation by splines, updating the planned data by observation tools in dynamics. The advantages of the STC method are as follows;
   1) Input data decreases largely in number by only defining trajectory of splines with via points and its attribute parameters.
   2) The STC method can drastically improve productivity and reduce cost and time. On the other hand, there exist several limitations to the site conditions for applying this method.
2. Blade controller system to bulldozer is available in wide range of general use, mainly working for land excavation, road pavement, large scale parking lot, snow-plow at street, field grading and ground decontamination in Fukushima.
3. The STC method is available in two ways; A) Speed control v/u generates new trajectory dy/dx (new land construction), B) Car driving v/u follows existing trajectory dy/dx (UAV).
4. By matching car speed steering/driving (v/u) with road plane curves(dy/dx), the STC method makes unmanned driving and inertial land navigation possible.

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