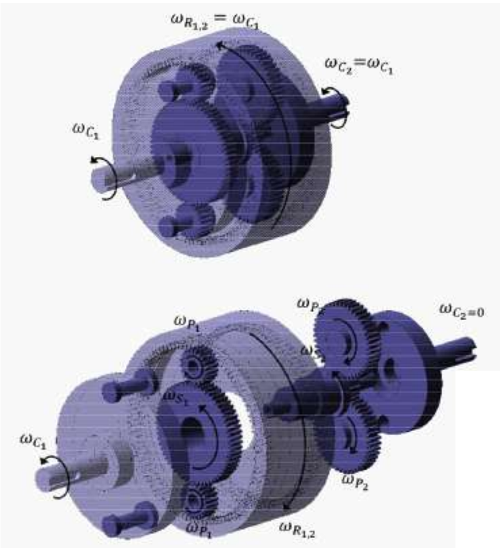
ISSN 1590-8844
Vol. 22 No. 01
2021

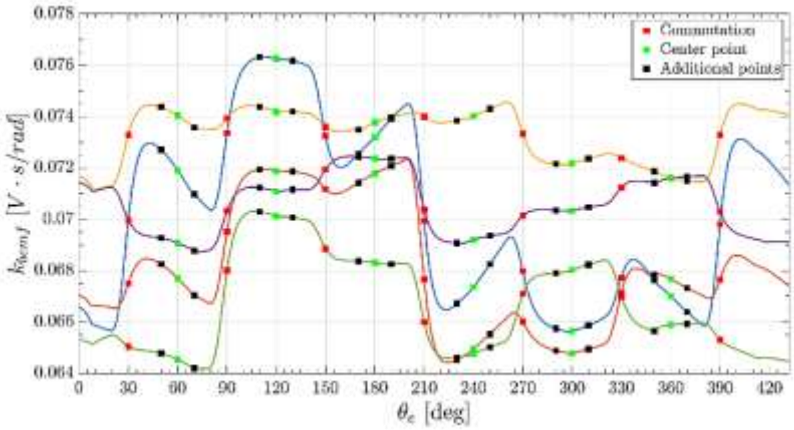
International Journal of Mechanics and Control

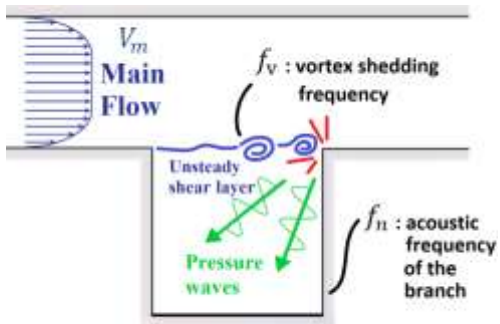
Editor: Andrea Manuello Bertetto

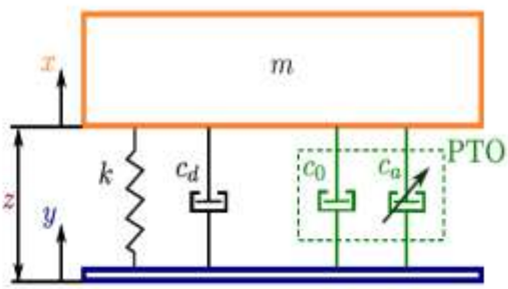
Scopus Indexed Journal

Reference Journal of IFToMM Italy
International Federation for the Promotion
of Mechanism and Machine Science









LIBRERIA EDITRICE UNIVERSITARIA
LEVROTTO & BELLA
TORINO

International Journal of Mechanics and Control

Associate Editors

Published by Levrotto&Bella – Torino – Italy E.C.

Official Torino Italy Court Registration
n. 5390, 5th May 2000

Deposito presso il Tribunale di Torino
n. 5390 del 5 maggio 2000

Direttore responsabile:
Andrea Manuello Bertetto

International Journal of Mechanics and Control

Editor: **Andrea Manuello Bertetto**

Honorary editors: **Guido Belforte**
Kazuo Yamafuji

General Secretariat: **Matteo D. L. Dalla Vedova**

The Journal is addressed to scientists and engineers who work in the fields of mechanics (mechanics, machines, systems, control, structures). It is edited in Turin (Northern Italy) by Levrotto&Bella Co., with an international board of editors. It will have not advertising.
Turin has a great and long tradition in mechanics and automation of mechanical systems. The journal would will to satisfy the needs of young research workers of having their work published on a qualified paper in a short time, and of the public need to read the results of researches as fast as possible.
Interested parties will be University Departments, Private or Public Research Centres, Innovative Industries.

Aims and scope

The *International Journal of Mechanics and Control* publishes as rapidly as possible manuscripts of high standards. It aims at providing a fast means of exchange of ideas among workers in Mechanics, at offering an effective method of bringing new results quickly to the public and at establishing an informal vehicle for the discussion of ideas that may still in the formative stages.

Language: English

International Journal of Mechanics and Control will publish both scientific and applied contributions. The scope of the journal includes theoretical and computational methods, their applications and experimental procedures used to validate the theoretical foundations. The research reported in the journal will address the issues of new formulations, solution, algorithms, computational efficiency, analytical and computational kinematics synthesis, system dynamics, structures, flexibility effects, control, optimisation, real-time simulation, reliability and durability. Fields such as vehicle dynamics, aerospace technology, robotics and mechatronics, machine dynamics, crashworthiness, biomechanics, computer graphics, or system identification are also covered by the journal.

Please address contributions to

Prof. Andrea Manuello Bertetto
PhD Eng. Matteo D. L. Dalla Vedova

Dept. of Mechanical and Aerospace Engineering
Politecnico di Torino
C.so Duca degli Abruzzi, 24.
10129 - Torino - Italy - E.C.

www.jomac.it
e_mail: jomac@polito.it

Subscription information

Subscription order must be sent to
the publisher:

Libreria Editrice Universitaria
Levrotto&Bella
C.so Luigi Einaudi 57/c – 10129 Torino – Italy

www.levrotto-bella.net
e_mail: info@levrotto-bella.net
ph.: +39 011 4275423
mob.: +39 328 5369063
fax: +39 011 4275425

International Journal of Mechanics and Control

Scientific Board

Published by Levrotto&Bella – Torino – Italy E.C.

Official Torino Italy Court Registration
n. 5390, 5th May 2000

Deposito presso il Tribunale di Torino
n. 5390 del 5 maggio 2000

Editor in Chief

Direttore responsabile:
Andrea Manuello Bertetto

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 22, No. 01, 2021

DESIGN AND SIMULATION OF AN ELECTRIFIED DIRECTIONAL DRILLING MACHINE

Luca Pugi* Lorenzo Berzi* Francesco Grasso** Raffaele Savi*** Valerio Vita*

* Dept. Of Industrial Engineering, University of Florence, Florence, Italy, luca.pugi@unifi.it; lorenzo.berzi@unifi.it; valerio.vita@stud.unifi.it

** Dept. of Information Engineering, University of Florence, Florence, Italy, Francesco.grasso@unifi.it

*** EGT SRL, Parma, Italy, r.savi@egt.it

ABSTRACT

Directional drilling machines are meeting an increasing favour since they allow trenchless underground installation of ducts, pipes, and wires. All these underground infrastructures are quite fundamental for the development of modern urban communities. A new generation of electric directional drilling machines are proposed in this work. These electrified machines introduce specific improvements in terms of performances, functionalities, and environmental sustainability. In this work simplified models for preliminary sizing and design of the machine are introduced. Same models are also useful to improve machine calibration also exploiting data that can be easily acquired from drives of electric actuators.

Keywords: Directional Drilling; Mechatronics; Electrification of Heavy Working Machines

LIST OF ADOPTED SYMBOLS (in order of appearance)

W_{tot}=Total Power delivered to drilling/excavating tools;
W_{drill} =Power need by the tool drill the soil
$W_{friction}$=Power that is dissipated by drilling rods an tools, due to friction whith walls of the surrounding bore/cavity
W_{rotary}=Power provided by the rotary motor to rotate drilling rods
W_{mast}=Power that is provided by the mast to control the longitudinal advance of drilling rods
W_{rd}=Power provided by rotary that is really used by the tool to drill the soil
W_{rf}=Power provided by rotary that is dissipated by friction on bore walls
W_{mf}=Power provided by mast that is dissipated by friction on bore walls
W_{hidr}=Power consumed to pump the lubricant fluid in to the drilled bore
W_{md}=Power provided by mast that is really used by the tool to drill the soil
F and M = friction forces and torques calculated in different sections of the bore.
dL= infinitesimal length of integrated rod section
w=linear density (weight over unit length) of drilling rod
α=inclination of the drilling rod
μ=friction factor between bore walls and rod surface
β=reduction of friction effects due to lubricant flow
R=curvature radius of drilling rod
v=long. speed of the rod along the bore
r=radius of the drilling rod
ω=rotational speed of drilling rods
SE=specific drilling energy
V=volume of drilled/excavated material
A=bore area
η_{tool}=drilling efficiency of the tool
W_{ideal}=ideal drilling powerl
W_{drill}=real drilling power
P=long. force on tool
T=torque on tool
k_{power}= ratio between mast and rotary drilling power
c_{hidr}=ratio between lubricant flow and corresponding volumes of drilled material
W_{hidr}=pump power
η_{pump}=pump efficiency

Contact author: Luca Pugi

Dept. of Industrial Engineering, Via di Santa Marta 3 50139 Firenze, ITALY
E-mail: luca.pugi@unifi.it

$X_{i\text{-}max}$=max. longitudinal force that is transmissible by the i-th track
τ_{max} =max tangential stress that can be trasmissed between track and soil
A_{track}=contact area of the track
c, φ= specific cohesion and angle of the Mohr Coloumb model
p_{track}=specific pressure of the track
s=slip of the track respect to ground
x=longitudinal position
k=slip scaling factor
r_{track}=rolling radius of the track
ω_{track}=angular speed of the track
v_{track}=long. speed of the track
l,b= length and width of a track
m=mass of the vehicle
R_{TOT}, R_{tot_i}=total motion resistance of the vehicle and total resistance of the i-th track
α_v=ground slope
R_{1_i}=girdle resistance of i-th track
R_{2_1}=aerodynamic resistance of i-th track
R_{3_1}=rolling resistance of i-th track
R_{4_1}=curve resistance of i-th track
m_i=inertial mass of the vehicle
C_R_i =torque on i-th track
X_i=longitudinal forces on i-th track
I, I_{track}=vehicle and track moment of inertia
r_{track}=radius of the track
L_{tot}=total length of the drilling rod
n_d=number of inertial elements used to simulate the torsional behavior of drilling rods
I_d, K_t, C_t= values of lumped inertia, stiffness and damping adopted in lumped torsional model of drilling rods

1 INTRODUCTION

Trenchless excavation [1] plays a key role for both maintenance and rapid construction of underground infrastructures that are fundamental for the development of “smart cities”[2]. There is a wide literature [3],[4], that recommends trenchless excavation techniques respect to conventional ones. Directional drilling is quite useful to operate in urban environments, since it assures a better sustainability and a reduced environmental especially when the construction yard must be integrated in a territory with pre-existing infrastructures[5].
As visible in figure 1, the most common excavation process can be divided in three phases:

- first, a pilot bore o small diameter is excavated (a);
- then the bore is enlarged with a single reamer or with multiple tools that should be used in sequence to gradually increase the overall diameter of the duct/tunnel (b);
- finally (c) a pipe is drawn consolidating in a definitive way performed excavation.

This sequence of operations is the most commonly adopted; one of the alternative excavation techniques that should be used is the “so called” wireline which is more often adopted for vertical excavations at high depth. In this case excavation is performed with a hollow pipe. Excavation or Sampling Tools at the bottom of the pipe are exchanged or moved through wire connections. In this work author focused their attention on the design of an electrified machines that can be easily used, also, but not only, in urban environments.
Respect to current state of the art, following innovative contributions are proposed and investigated:

- Complete Machine Electrification: an electrified machine should be far much more efficient respect to a conventional one with a conventional hydraulic transmission especially at partial loads even considering current improvement in the management of electro-hydraulic units[6][7]. Machine proposed in this study is the first “Full Electric” directional drilling machine which substantially removes any fluidic transmission that is still adopted even in most modern electro-hydraulic solutions that are often defined as “electric” since the pump of a flow controlled hydraulic actuator is controlled by a vector controlled, electrical motor.
- Sustainability: Carbon Footprint of an electrified machine is quite better respect to conventional machines[8]
- Identification and Monitoring of Drilling Process: electric drives that are used to control each actuator of the machine provide data related to speed, torque, and power consumptions. These data are useful not only for a complete monitoring of the machine but also to identify and optimize the excavation process respect to features of soil and adopted tools [9].

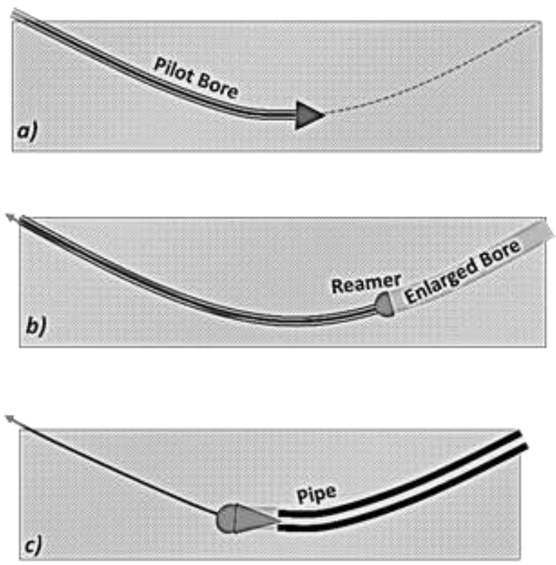


Figure 1 Trenchless excavation phases, (a) pilot bore, (b) reaming, (c)pipe is finally inserted/pulled.

In figure 2 it is represented a typical scheme of a directional drilling machine: it is tracked vehicle to assure a limited movement capability which is necessary for installation and transportation; excavation is performed by a rotating toll which is moved by two actuation stages, respectively called the “rotary” one and the “mast” one. Rotary provides the cutting rotational motion while the mast is responsible of the longitudinal advance of the tool in the ground.

Since the mast has a limited run, drilling rods are periodically added until desired drilling length/depth is reached.

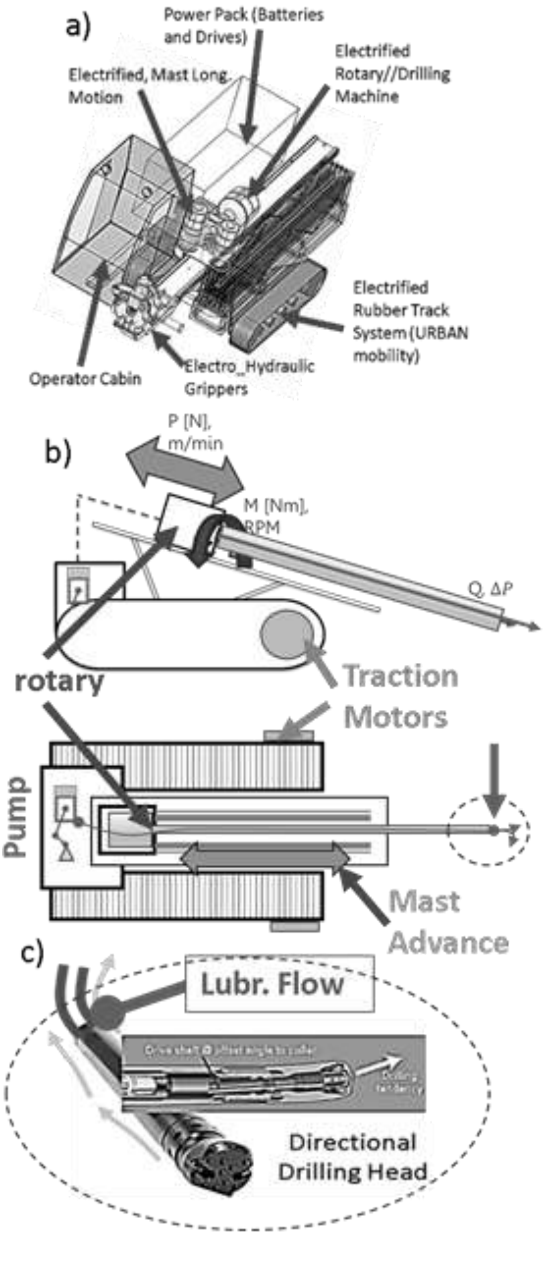


Figure 2 Main components of the machine(a), side and top view(b), detail of directional drilling head(c)

Assembly of drilling rods is automated: auxiliary grippers hold the rods while rotary provide the torque needed to screw and unscrew them.

Length of drilled bore it is thousand times longer (hundreds or even thousands of meters) respect to tool diameter (variable from 40 to 150 millimetres).

So, removal of excavated material is managed using a pressurized fluid which also lubricates and cools the tool.

The same pressurized lubricant is also used to guide cutting head trajectory: flow of fluid returning to surface, ensures centring of the tool in the bore; so, the same flow, if properly managed, can be used to contribute to the control of the trajectory of the drilling head.

An external pump provides this lubricant flow with pressures of several bars (20-100bar). Delivered flow is high, from 3 to 5 times the volumetric rate of excavated material. For these reasons, power demanded by the pump is high and often comparable to energy consumptions of rotary actuator. Considering pump power demand, pressure of lubricant fluid and its fundamental role in directional drilling process, it should be argued that this pumping unit plays a key role in determining a proper design and a successful use of the machine.

In this work authors investigate the possibility of electrifying all these actuation stages exploiting features of models that are proposed for this purpose.

Adopted design approach, that is quite general, is applied to benchmark test case of Table I which was suggested by the industrial partner of this project E.G.T. SRL. Data of Table I are also the specifications of the machine prototype that has been produced and tested, as final output of the research project.

Table I - preliminary specifications of the machine

Parameter	Value
Approx. Torque Load specifications (Rotary)	9000-1500[Nm] at 30-190[rpm]
Long. Loads (Mast)	120000[N] at 0.83[m/s]
Approx. Weight of the Machine	15-20 tons

The model that is used to properly size most of machine subsystems, is organized in the following way:

- A model of the drilling process is proposed for the sizing of involved powertrains and actuators such as rotary, mast and pumping units.
- A simplified model is introduced to size the traction system.
- A State Machine implemented with Matlab-Simulink Stateflow™ is used to reproduce machine workflow in different conditions. In this way it is possible to reproduce a typical mission profile of the machine. This realistic power profile is used for a proper sizing of energy management system and batteries.

2 DRILLING MODEL

Total power delivered to excavating tool W_{tot} is evaluated as the sum of two contributions W_{dril} and $W_{friction}$ (1):

- W_{dril} is the power which is needed to drill the ground.
- $W_{friction}$ is the additional amount of power that is lose due to friction of rotating rods and drilling tools with surrounding bore walls.

$$W_{tot}=W_{drill}+W_{friction} \quad (1)$$

Power W_{tot} can be also expressed as the sum of the power delivered by different motors/actuators (2):

- W_{rotary} is the power provided by the rotary to rotate the toll;
- W_{mast} is the power provided by mast motor to pull or draw the toll in the ground. Signs of advance speed and needed efforts are variable according performed operations.

$$W_{tot}=W_{rotary}+W_{mast} \quad (2)$$

Both mast and rotary power should be considered as the sum of corresponding drilling and friction contributions (3):

$$W_{rotary}=W_{rd}+W_{rf}$$
$$W_{mast}=W_{md}+W_{mf} \quad (3)$$

In (3) the first subscript is used to describe if power contribution is related to rotary (r) or to mast (m) while the second one is use to specify if power is allocated to drill the ground (d) or dissipated as friction (f) along bore walls.
The relevant amount of power that has to be provided to the pumping unit of the lubricant fluid is indicated as W_{hidr}.
As previously said this contribution is often equal or greater than W_{rotay} so this contribution should be considered and added to W_{tot} to evaluate total power consumptions of the machine.

2.1 FRICTION AND WEIGHT RELATED POWER CONSUMPTIONS

Contributions due to friction on bore and weight of the rod are calculated exploiting the so called soft-string approach [10]: flexible stiffness of the drilling rod is neglected; according to the scheme of figure 3/a it is possible to calculate the behaviour of friction pulling forces F in straight or curved sections of the bore.
In particular, α represent the local angular orientation of bore section while dL and R are respectively the length of considered section and the local curvature radius.
Behaviour of F is calculated integrating differential functions (4) along the length of the rod:

Curved Bore
$$dF = \beta w R(\sin(\alpha)+\mathrm{sign}(v)\mu \cos(\alpha))d\alpha \quad (4)$$

Straight Bore
$$dF=\beta w (\sin(\alpha)+\mathrm{sign}(v)\mu \cos(\alpha))\, dL$$

In (4) it is assumed a linear weight of the drilling rod w(weight of the rod/unit length) and a factor β that take count of the lubrication reducing friction coefficient μ.
The sign of the friction contribution depends on the sign of the longitudinal speed v of the rod respect to bore.
Same model is also used to calculate the friction torque M: it is supposed that normal forces on bore walls produce a friction torque which is proportional to the radius r of the rod.
Resulting toque along the rod can be calculated integrating differential functions (5) along the length of the rod:

Curved Bore
$$dM = \mu r\beta(wR\cos(\alpha) -F)d\alpha$$
(5)

Straight Bore
$$dM=\mu r\beta w\cos(\alpha)\, dL$$

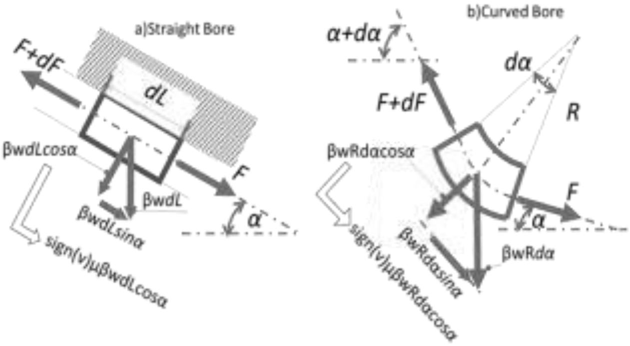


Figure 3 Calculation of longitudinal push and pull forces along straight and curved bore sections.

Once friction forces are calculated, corresponding friction powers are calculated according (6) and (7), knowing both rotary and mast speed, ω, v.

$$W_{rf}=M\omega \quad (6)$$

$$W_{mf}=Fv \quad (7)$$

2.2 DRILLING POWER

Specific cutting energy SE[11] represents the amount of energy that have to be spent to excavate an unitary volume of material. SE is a specific property of excavated material and can be evaluated from literature or from specific experimental tests. Also, SE is approximately equal or at least proportional (8) to the compression resistance of the material σ_{compr} [11].

$$SE=E/V[\mathrm{kwh\ m^{-3}}]=\sigma_{compr} \quad (8)$$

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 22, No. 01, 2021

Drilling power W_{drill} (9) is supposed to be proportional to specific energy and to the rate of excavated material which can be calculated as the product of advance speed v and the excavated section A. Since the drilling process is performed by a real tool, this process is affected by additional losses which are modelled by introducing the so called "tool efficiency" which is defined as the ratio between the minimum, ideal power required to excavate the material W_{ideal} and the real one W_{drill} (10)

$$W_{drill}=SE\ A\ v\ \eta_{tool}^{-1} \tag{9}$$

$$\eta_{tool}=W_{ideal}/W_{drjll}=\mathrm{SE}\ A\ v\ W_{drill}^{-1} \tag{10}$$

Once W_{drill} is calculated, it is possible to represent it as the sum of mast and rotary contributions W_{md} and W_{rd} according (11)

$$\begin{aligned} &W_{drill}=W_{md}+W_{rd} \\ &W_{md}=P/A \\ &W_{rd}=T\omega/(vA) \end{aligned} \tag{11}$$

In (11) following symbols are adopted:

- P is the longitudinal thrust on the tool;
- T is the torque applied on the tool;

it is possible to define k_{power} as the ratio between the power delivered by the mast and the one of the rotary (12):

$$k_{power}=W_{md}/W_{rd} \tag{12}$$

According to literature [12], most of the power is absorbed by the rotary [13]; typical value of k_{power} are between 0,001 and 0,1[14].

2.3 POWER OF THE PUMPING UNIT

According overcited literature the flow of water Q, needed to lubricate the tool and to remove excavated material is described by (13):

$$Q=c_{hidr}Av \tag{13}$$

Coefficient c_{hidr} is variable according to different parameters such, as example, material porosity, or length of the drilled bore, however typical values are between 3 and 5 with a mean expected one equal to 4.

Flow is substantially imposed by the pump which is typically a speed controlled volumetric machine.

So, corresponding pressure Δp of injected water varies according to the hydraulic losses along the drilled bore: typical values are around 30-40bar; however, in some situations even pressures of 70-80 bar can be recorded. Power needed by the pump W_{hidr} can be calculated according (14):

$$W_{hidr}=Q\Delta p/\eta_{pump} \tag{14}$$

2.4 PRELIMINARY SIZING OF MAST AND ROTARY MOTORS

Sizing of motors is performed considering a known testing/operating condition which is often defined "constant weight on bit" test: a known value of P is applied while drilling the soil. Then drilling tests are repeated changing advance and rotational speed v and ω exploring cutting conditions in which the value of k_{power} is variable.

As example in figure 4 it is considered an example with a constant value of P of 20000N to which some design constraints are applied:

- Maximum value of k_{power}: value of k_{power} depends on the nature of excavated soil. However even for very soft materials k_{power} is usually much lower than 0.1 since most of the drilling power is usually delivered by the rotary. For performed calculations a constant tool efficiency of 0.35 is considered[10].
- Limitation of rotary speed ω: rotary speed is limited as some features of used tools and performed operations are known. As example in figure 4 it is supposed the usage of a tool with an external diameter of 200mm to ream a pilot bore with an initial diameter of 80mm. According features of simulated reaming some maximum and minimum speed limits should be imposed.
- Pressure and lubricant flow limits: according (13) the flow of lubricant must be proportional to the volume removal rate of excavated material. In this work it is considered a mean value of c_{hidr} equal to 4 (for each dm^3 of excavated material, four litres of water are injected). So maximum advance speed of the tool is limited by performances of the pump used to inject the lubricant fluid.

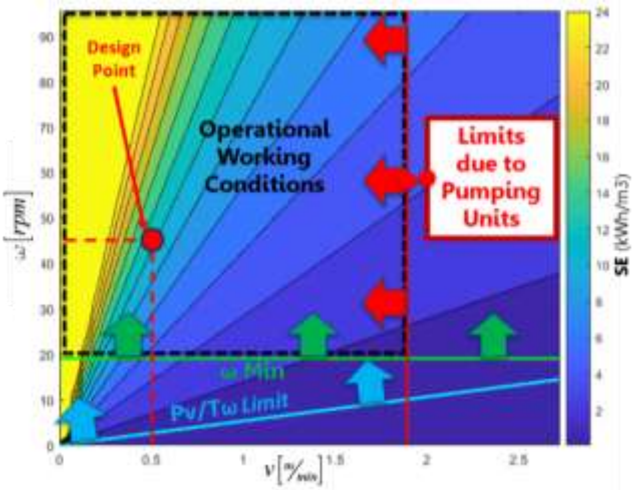


Figure 4 Specific SE with a constant P value of 20000[N]

Considering, overcited constraints, it is possible to identify an area of feasible operational points.

Calculations are repeated for different values of P to perform an approximate sizing of motors in terms of torque and power performances.

Despite to introduced approximations this procedure is accurate enough to perform a preliminary choice of motors and gearboxes. This sizing is further refined considering limitation arising from system encumbrances and limited availability of commercial components among to which choice can be performed.

In figure 5 and 6 chosen actuators for both rotary and mast units are shown.

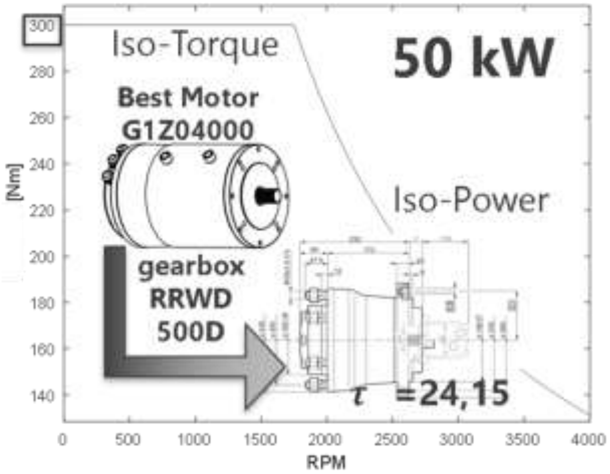


Figure 5 Example of chosen motor and gearbox for the rotary unit.

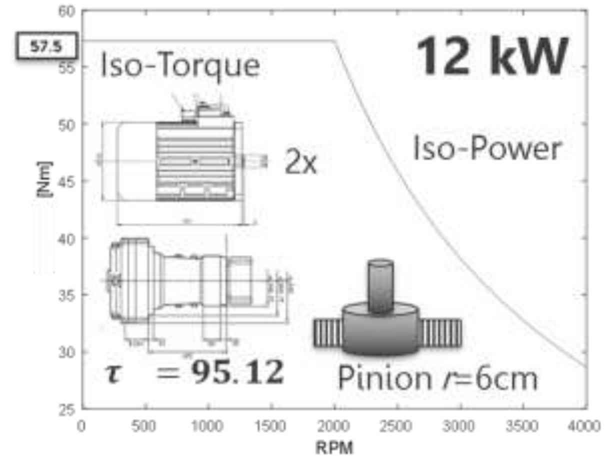


Figure 6 Example of chosen motors and transmission for the mast unit.

2.6 PERFORMANCES ACCORDING TO MOTOR AND TOOL BEHAVIOUR

It is possible to evaluate the effect of additional constraints introduced by torque and power limitations of motors.

Calculations take count also of tool efficiency[10] which is assumed to be constant and equal to 0.35.

Respect to previous model also the contribution of friction losses is considered.

For what concern the calculation of friction losses different bore lengths (0 and 200 meters) are considered. For what concern simulated drilling operations they are the same that have been previously adopted to produce figure 4 (same tool, same reaming operation). Some results are shown in figure 7: optimal performance of the chosen motor is obtained for a rotation speed of about 80rpm; this is especially true for long drilling lengths and soft materials since in these conditions friction losses are more relevant.

Also, limitations due to performances mast motors and available coolant flow are considered; for investigated configuration of figure 7, most restrictive limitations are related to lubricant pumping unit. Results of figure 7 can be further refined considering a variable tool efficiency: it is considered a known tool and its efficiency is mapped respect to advance and rotational speed $\eta_{tool}(v,\omega)$.

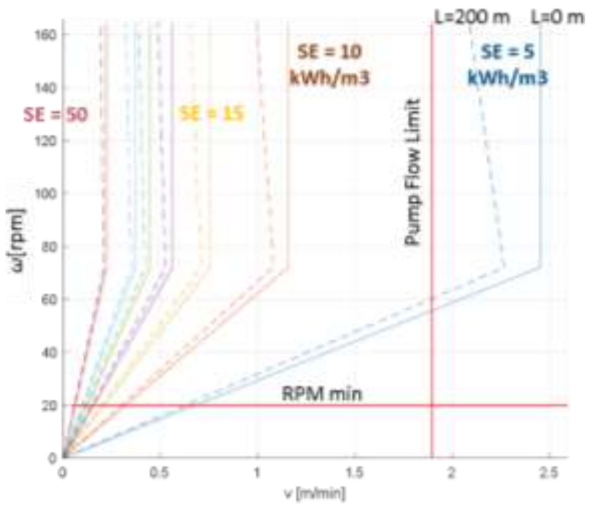


Figure 7 Working constraints introduced by motor performances for a short bore(continuous line, L=0) or a long one (dashed lines L=200m)

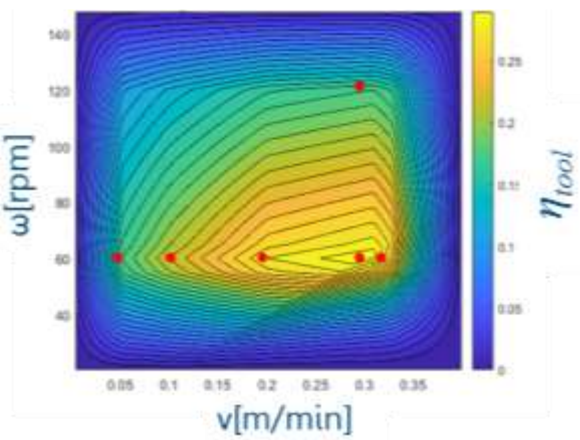


Figure 8 Simplified $\eta_{tool}(v,\omega)$ efficiency mapping from examples taken from literature[14], red points are experimental data used to produce the interpolating surface.

In figure 8 some results are shown: tabulated efficiency of the tool is evaluated according to data taken from literature [14][15]. Data visible in figure 8 are referred to a reaming operation performed with external diameter of bits of 21cm, excavating a soil with a specific energy SE of about 25kWh (compact sandstone). For this tool, some experimental data were available (six measured operational conditions) that are represented as red-dots markers in figure 8. These data are used to perform a model-based extrapolation of tool efficiency which is also shown in figure 8 as a continuous surface. Authors believe that this limited base of experimental data should be further integrated with new field acquisition when the prototype of the proposed machine will be assembled. Indeed, one of the main advantages of a full electrified drilling machine is represented by the possibility of a continuous, reliable, and affordable monitoring of drilling parameters directly from electric drives of rotary, mast, and pumping unit.

This is a clear advantage since it allows the creation of a wide library of data that should be continuously updated in service. In this way it is possible to further optimize design and usage of the machine respect to different quality of soil, tools, performed operations.

It is possible to redraw the constrained operational capability of the machine described in figure 7 also considering tool efficiency mapping of figure 8; results are shown in figure 9: it is possible to investigate performances taking count of specific features of both machine and drilling tool, also considering the length of the bore *L*.

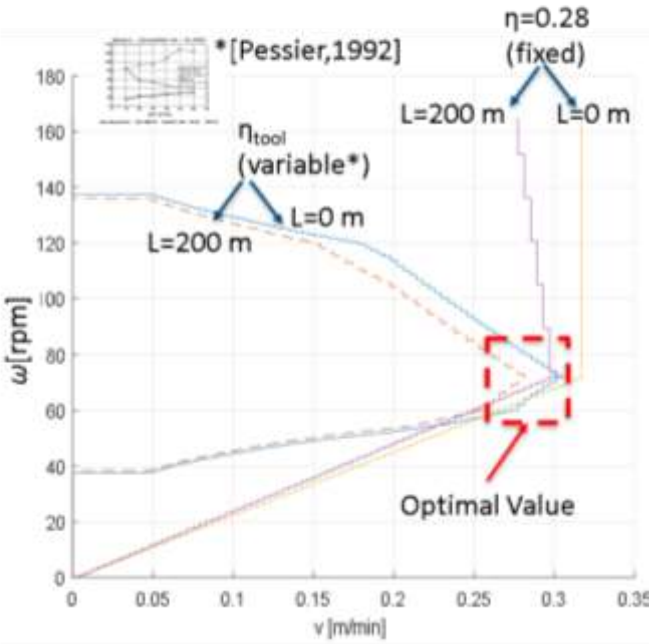


Figure 9 Working constraints introducing motor performances and tool efficiency according to recorded tool efficiency available in literature [14]

This approach is useful to obtain clear indications concerning both optimal design and usage of the machine:
as the advance ratio increases the range of admissible speed of the rotary decreases. So, to increase productivity it is very important a model-based optimization of drilling parameters calibrated with experimental data from field activities.

3 SIMPLIFIED TRACK MODEL

Directional drilling machines are equipped with a tracked traction system. Indeed, tracks are not designed for prolonged travels but only for the correct positioning of the machine within the construction yard.

To properly size the system and evaluate corresponding energy consumptions, it is adopted a relatively simplified model, the so called “Bekker Model”[16-18].

A brief scheme of adopted model is visible in figure 10: maximum longitudinal force that is transmissible by the *i-th* track $X_{i\text{-}max}$, is described by equation (15)

$$X_{i\_max}= \tau_{max} A_{track} \tag{15}$$

In (15) τ_{max} and A_{track} represent respectively the maximum tangential stress for the soil and contact area between track and ground.

Maximum tangential stress is calculated according to Mohr Coulomb Model (16) being *c* the specific cohesion of the ground and the corresponding angle φ

$$\tau_{max}=c+p_{track}\tan\varphi \tag{16}$$

Tangential effort τ is not saturated along the complete contact area but it is distributed along track length *x* according to relation (17) that is often referred in literature as the Janosi and Hanamoto, model:

$$\tau(x)= \tau_{max}(1-e^{sx/k}) \tag{17}$$
$$s=(r_{track}\omega_{track}-v_{track})/(r_{track}\omega_{track})$$

Janosi and Hanamoto, model (17) assumes that tangential effort varies only along the longitudinal direction according to an exponential law of the slip *s*; slip is scaled according the relative position along the track *x* divided respect to a scaling factor *k*.

Slip *s* is calculated as a function of peripherical and longitudinal speed of the track (ω_{track} and v_{track}).

Once $\tau(x)$ is known, longitudinal force of the i-th track X_i can be calculate as the corresponding integral along track contact area which have an equivalent length *l* and a width *b*(18):

$$X_i = b\int_0^l \tau dx \tag{18}$$

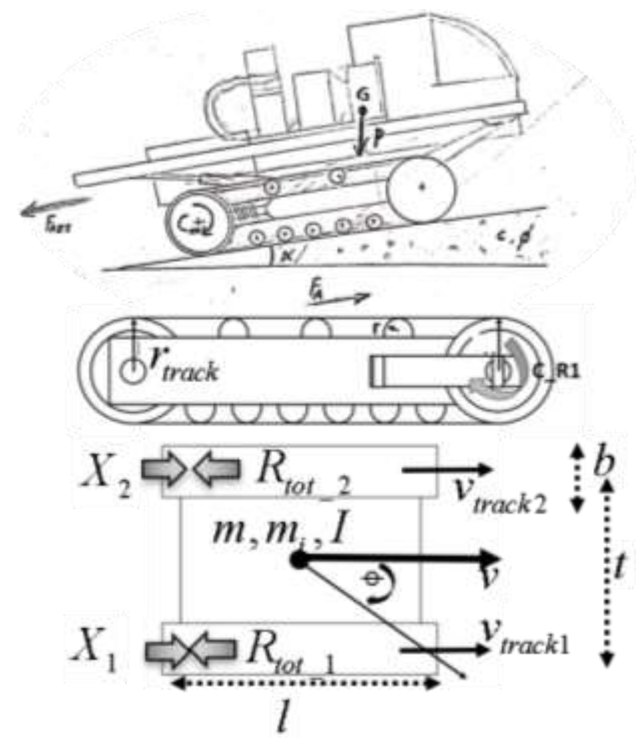


Figure 10 Simplified planar model of vehicle dynamics

Total motion resistance of the vehicle R_{TOT} is calculated as the sum of the contribution of each track R_{tot_i} and a third one due to ground slope α_v(19).
Track resistances R_{tot_i} are calculated according to an approach often proposed in literature [16].

$R_{TOT}=R_{tot\_1}+R_{tot\_2}+ mgsin(\alpha_v)$ (19)
$R_{tot\_i}=R_{1\_i}+ R_{2\_1}+ R_{3\_1}+ R_{4\_1}$
R_{1_i}=*girdle resistance*
R_{2_1}=*aerodynamic resistance*
R_{3_1}=*rolling resistance*
R_{4_1}=*curve resistance*

Vehicle dynamics is reproduced by a system of four equations (21-22):

- Longitudinal dynamics of vehicle body (20): longitudinal acceleration is calculated knowing motion resistances on tracks, traction forces and the contribution of vehicle weight due to slope α_v. Equivalent longitudinal inertia m_i is different respect to vehicle mass m to take count even approximately of rotating masses.
- Yaw dynamics of vehicle body (21): since vehicle speed is low, contribution of lateral forces is neglected; equilibrium against yaw rotation is considered. When vehicle performs a self-rotation with a null longitudinal speed v, additional resistances are added the term R_{4_i}.
- Track dynamics: to calculate traction forces X_1 and X_2 from (18) is necessary to estimate the slip of each track by solving for each track equation (22). C_R_1 and C_R_2 are the torques exerted on tracks; I_{track} is the rotational inertia of the track.

$$m_i\dot{v} = X_1 + X_2 - R_{tot_1} - R_{tot_2} - mg\sin\alpha_v \tag{20}$$

$$I\ddot{\varphi} = (X_2 - X_1 - R_{tot_1} + R_{tot_2})\frac{t}{2} \tag{21}$$

$$\begin{aligned} I_{track}\dot{\omega}_{track1} &= C\_R_1 - X_1 r_{track} \\ I_{track}\dot{\omega}_{track2} &= C\_R_2 - X_2 r_{track} \end{aligned} \tag{22}$$

Proposed model of track dynamics is used for the sizing of traction motors considering vehicle data described in Table II. Torque behaviour of proposed motors is described in figure 11: each motor has a nominal power of about 10kW, so the total installed power is about 20kW.

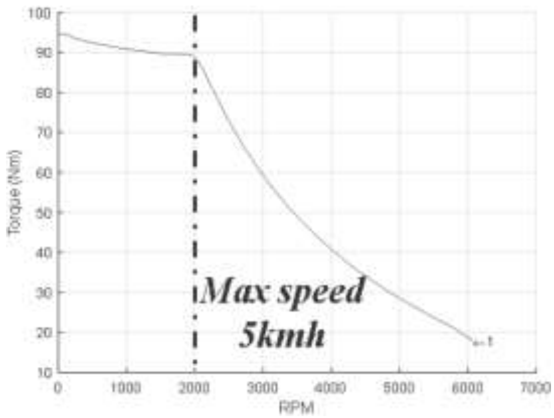


Figure 11 Torque behaviour of chosen induction motor

Table II - Dimensions and specifications

b(track width)	0,3 m	r_{track}	0,2 m
l(track length)	1,975 m	*Max Speed*	5kmh
m(vehicle mass)	7.5tons	*Max Slope*	30%

4 SIMULATION OF A FULL MISSION PROFILE

Authors also developed a full dynamic model of the whole machine. Resulting model is briefly described in figure 12: for every model previously described in previous sections authors implemented a Matlab-Simulink™ instance.
In this way each module is implemented in a separate model giving the possibility of different customized integrators and sampling frequencies optimizing the model both in terms of realism and required numerical resources.
Low order, fixed step integrators with low sampling frequencies are used to implement models of controllers and digital subsystems.
Variable Step Solvers with stiff/robust or fast solvers are instead used to integrate models of continuous physical subsystems. Also, the adoption of model instances assures the possibility of an easy customization of the model since each functionality can be modelled or simply implemented in a different way with limited or null consequences on the other parts of the model. Data exchange between model instances is performed with virtual connections like labels for synchronous communication between blocks.

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 22, No. 01, 2021

Shared memory variables are employed for asynchronous data exchange between different blocks also assuring a faster and more efficient exchange of logic//process variable between different blocks. All the submodules of the model are coordinated through a state-flow™ logic, which proved to be the best solution to simulate different working cycles. Improved efficiency of the code is obtained alternatively enabling or disabling the integration of sub-system according their real dynamics and use; so any part of the algorithm is executed only when necessary: for example while the machine is drilling, the model of the traction system is "disabled"; in this way this functionality is still implemented in the model but it doesn't contribute to the overall computational loads when it's output is not required being not or partially executed. This implementation is also quite optimal for a real time execution of the model or of a part of it for testing activities since this approach is directly derived from previous experiences concerning real time modelling of steam plants [19] and automotive mechatronic sub systems [20]. In figures 13/a and 13/b, an example of working cycle is shown: major attention is focused on the reaming phase which proved to be the more demanding for the simulated mission profile.

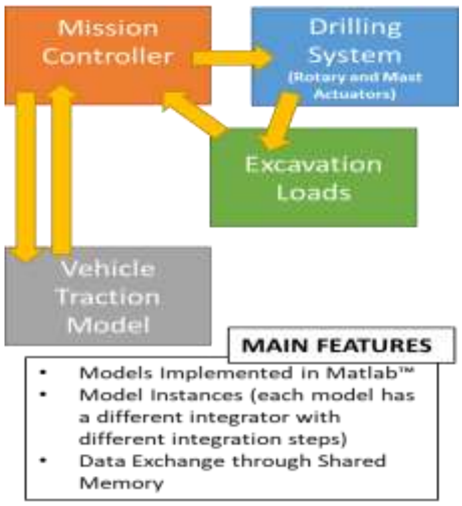


Figure 12 Simplified planar model of vehicle dynamics.

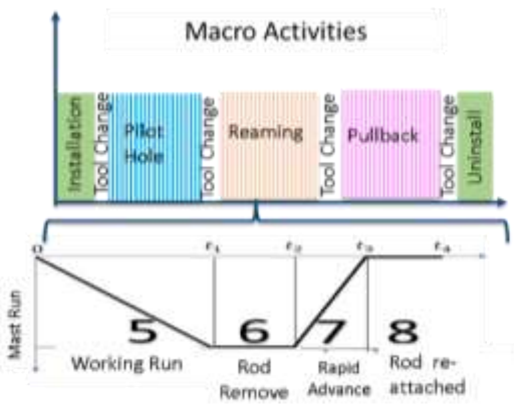


Figure 13/a Example of working cycle

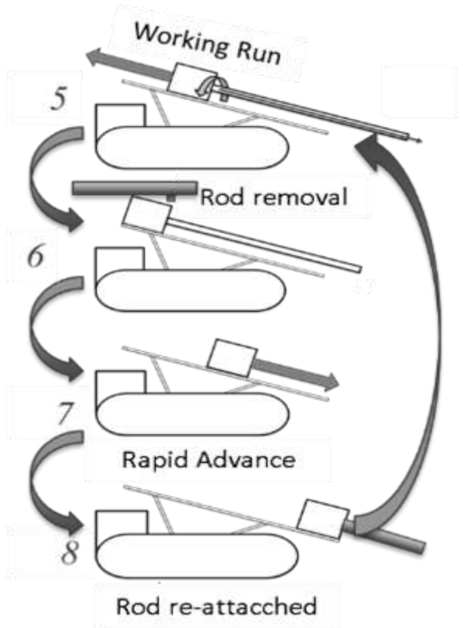


Figure 13/b Description of the five working phases of the bench work cycles of figure 13/a

4.1 TORSIONAL BEHAVIOR OF DRILLING ROD

Considering the length of excavated bores (hundreds of meters) respect to the diameter of drilling rods, torsional behavior of the system cannot be completely neglected.
Also, data that are used to calibrate the model should be produced according different test procedures or different approaches so the procedure that is used to calibrate the model must be customized.
Authors further improved the model of the drilling process described in section 2 adding the following features:

- A discretized model of the torsional behavior of drilling rods is implemented. The number of considered torsional degree of freedom can be customized.
- Different implementations of the drilling loads of mast and rotary units: exploiting the overcited method of model instances is possible to choose the way in which drilling loads are calculated or interpolated from experimental data.

As visible in figure 14, drilling rods are modelled as a torsion bar of length L_{tot} which is discretized in a customizable number n_d of lumped inertial element (torsional inertia I_d) connected by visco-elastic elements (equiv. stiffness and damping K_t, C_t). On each lumped inertial element is also applied a part of the total friction force that is calculated according to the model described (5) and (6).
Torsion behavior is modelled with a fixed number of degree of freedom so the number of simulated torsional modes is constant during a simulation; for the same reason, calculated eigen frequencies are variable during a simulation.

Both inertia and compliance of rods are proportional to the total length L_{tot}, so eigen-frequencies are inversely proportional to L_{tot}.
Torsional behavior is implemented using a State Space representation so the number of implemented degrees of freedom can be easily modified with simple and almost automated procedure. Fastest simulations are performed reducing the number of discretized rod sections n_d to 1.

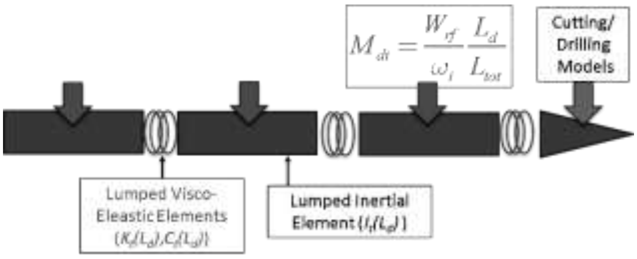


Figure 14 Lumped torsional model of the drilling rod.

4.2 EXAMPLES OF SIMULATION RESULTS

Proposed model was used to perform several simulations.
Simulations shown in this section are referred to the reaming (outer diameter 20cm, inner one 8cm) of a soil with a low specific energy SE of about 10kWh (Claystone, as example).
Most of the examples in this work are referred to reaming simulations for the following reasons:

- This working phase is the most demanding in term of machine performances.
- Reaming is associated to the highest material removal, so also in terms of overall energy consumptions is the most demanding phase.

For this benchmark test case it is chosen a soft soil (claystone) mainly for two reasons:

- This kind of soils are statistically quite common.
- Soft soils allow high advance speed and material rate removal. In this conditions, performances of the drilling machine really affect productivity of performed process.

High material removal involves higher energy consumptions since power required by mast, rotary and pumping units are proportional to material removal rate.
In figure 15 some results referred to the reaming of a 200m bore are shown: model is able to predict a feasible physical behaviour in terms of required power for rotary mast and pumping units.
For what concern rotary unit required power is nearly constant (only slightly decreasing) since most of the power required derives from the cutting process being the bore well lubricated thank to the high value of c_{hidr} (a value of 4). This high lubricating flow is unavoidable to assure a high advance speed.
Also, the power delivered by the mast unit is only slightly decreasing for the same reason: for a straight, well lubricated bore, most of the required power is related to the drilling process.

Finally, power delivered by the pump is strongly decreasing respect to tool advance: delivered flow of lubricant is constant, but the corresponding pressure drop is proportional to the distance that lubricant must cover to arrive to the drilling tool and return outside. To evaluate energy consumptions a constant efficiency of electrical drives is considered. As consequence the total power that must be delivered to the machine is decreasing respect to the advance of the tool. Periodical Fluctuations on consumed power are visible in figure 15. These fluctuations are due by the need of interrupting the drilling phase to remove rods as the tool is gradually extracted by the soil. In figure 16 it is shown the behaviour of the mast run to periodically remove drilling rods during the reaming phase.

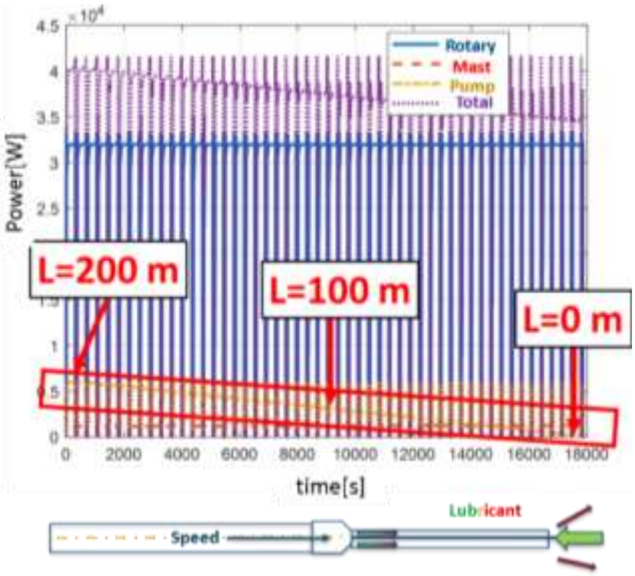


Figure 15 Simulation of required power behaviour during the reaming of a 200m bore.

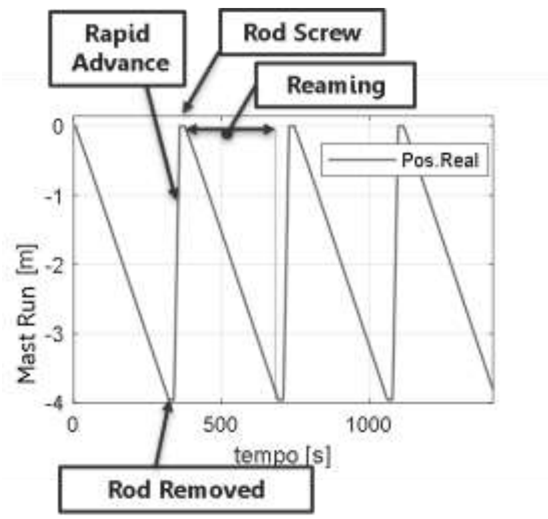


Figure 16 Detail of mast run profile.

Model is capable to correctly reproduce the physical behaviour of the system. In figure 17, it is shown the simulation of a blocking of the tool due to excessive drilling loads.

To simulate tool blocking the same reaming is repeated, but the following parameters are modified:

- A high specific energy of 30 kWh is considered (a very compact siltstone reamed with a sub-optimal tool)
- A very high desired advance (0.6m/min) is imposed.
- Null/negligible lubrication is applied.

As visible in figure 17, the simulated tool initially begins to advance, then both advance and rotational speed decrease: required loads are too high blocking the tool; at the end both mast and rotary are blocked: mast cannot advance since rotary is stopped while rotary cannot restart since very high pulling forces are applied by the mast and friction is blocking the tool.

This transient is heavily affected by torsional behaviour of drilling rods: for a simulated bore length of 200meters angular displacements along the rods are quite big as visible in figure 17.

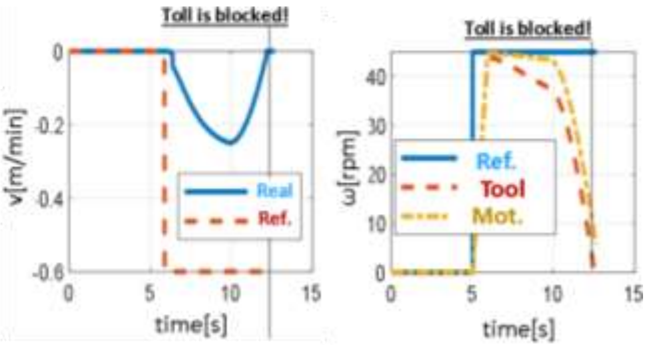


Figure 17 Simulated blockage of the tool.

4.3 SIZING OF ENERGY STORAGE SYSTEM

Starting from the work cycle described in figures 13/a/b it is possible to evaluate energy consumptions of various work phases. Sizing of the energy storage system is performed considering demanding scenarios like the one considered in figure 15. Obtained results in terms of hourly power are described in Table III. Higher power demands are associated to heavy reaming with high advance speed *v*: corresponding power consumptions of different loads are represented in figure 18. Working phases described in Table III are referred to the cycles of figures 13/a/b.

It should be considered the possibility of a working cycle in which mean power demand is about 20-25kW with instantaneous peaks of no more than 40-50kW.

With a total capacity of about 200kWh it is possible to foresee a continuous operational capacity of about 8hours. However, considering a common soil with an SE between 5-10kWh/m^3, with 8 hour of work it is possible to perform the drilling of several hundred of meters. So, it is quite common to have at least one or two hours of other phases in which the foreseen consumptions should be lower.

So, for a continuous medium//light working day, a capacity of about 100kWh is enough.

Finally, it should be considered the possibility of a floating charge of the battery while the machine is operating, since during the drilling phase is anchored in a construction yard where some small even residual power should be available.

As example 3-3.5 kW of single-phase AC power or 10kW of three phase power are quite reasonable values of available power even in a weakly infrastructure environment. As visible in Table IV and V, with a small available power available for recharge, it is possible to obtain a considerable extension of machine autonomy even considering a small battery pack of 50kWh.

A correct sizing and a proper use of the battery pack are very important, so authors are currently evaluating the application of different estimation techniques of both SOC (State Of Charge) [21] and SOH (State Of Health) [22].

Table III - Energy Demand

Work Phase	Min Hourly Energy Demand	Max Hourly Power Demand
Installation	5kWh	10kWh
Pilot Bore	10kWh	20kWh
Reaming	20kWh	32kWh
Pullback	5kWh	20kWh
Uninstall	5kWh	10kWh
Tool Change/ /Setup	0kWh	2kWh

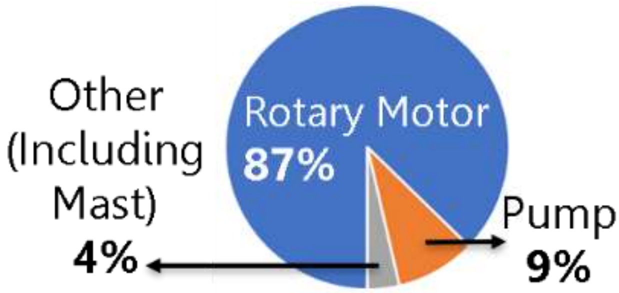


Figure 18 Distribution of energy consumptions of different motors and subsystem during a heavy reaming.

Table IV - Modular Sizing and Expected Machine Autonomy for Normal Load Cycle (expected Mean Load of 25kW)

Battery Size	Machine Autonomy (hours)		
	No Floating Charge	3.5 kW of Floating Charge	10kW of Floating Charge
50[kWh]	2h	about 2h 15I	3-4h
100[kWh]	4h	about 4h 30I	6-7h
150[kWh]	6h	7h	10h
200[kWh]	8h	9h	14h

Table V - Modular Sizing and Expected Machine Autonomy for Light Load Cycle (Expected Mean Load of 15kW)

Battery Size	Machine Autonomy (hours)		
	No Floating Charge	3.5 kW of Floating Charge	10kW of Floating Charge
50[kWh]	3h	4h	10h
100[kWh]	6h30I	8h	20h
150[kWh]	10h	12h	30h
200[kWh]	14h	17h	40h

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work authors have presented a modular model of an electrified drilling machine.

Proposed model has proven to be useful for the design a first prototype of the proposed machine showing the overall feasibility of the proposed solution.

Proposed methodology is general, and it can be applied to the design of machines of different size.

This is very useful for a standardized industrial production.

As future extension of this work authors will follow the experimental testing activities of the machine with EGT SRL. Experimental data should be very useful to further refine machine design and to better calibrate proposed drilling models.

Authors are verifying the possibility of a further refinement of motor control to better control the torsional behaviour of the tools and drilling rod, starting from previous works of Tashakori [23]. For what concern torsional behaviour, a proper evaluation of damping plays a key role in determining accuracy of performed simulations, so authors are also investigating the possible implementation of more realistic friction models especially for what concern the interface between drilling rods and excavated bore.

For what concern friction models, there is a wide literature [24] ranging from the widely diffused approach proposed by Karnopp [25]to other contributions of Quinn [26] and Dahl [27]. Introduction of more complex friction models should be carefully evaluated considering known consequences on the way in which the system is controlled[28]. In this sense recent contributions of Borello [29] and Kikuuwe [30] should be very useful especially for what concern overall numerical stability of simulated friction system respect to numerical troubles arising related to multi-quadrant operations or to efficient implementation with fixed step solvers.

REFERENCES

[1] Gerasimova, V. (2016). *Underground engineering and trenchless technologies at the defense of environment*. Procedia engineering, 165, 1395-1401.276-287. DOI: 10.1016/j.triboint.2018.06.014

[2] Marchant, P. (2018). *Repair or Replace: Technologies Available for Trenchless Remediation*. Water Scarcity and Ways to Reduce the Impact: Management Strategies and Technologies for Zero Liquid Discharge and Future Smart Cities, 197.

[3] Chothe, O. K., & Kadam, V. S. (2016). *Comparative Study of traditional method and innovative method for Trenchless Technology: A Review.* International Research Journal of Engineering and Technology, 3(05).

[4] Lindsay Ivey Burden (2015),"*Synthesis of Trenchless Technologies*", virginia center for transportation innovation and research,Pg.No.1-25

[5] Ariaratnam, S. T., & Beljan, I. J. (2005). *Postconstruction evaluation of horizontal directional drilling installations*. Practice Periodical on Structural Design and Construction, 10(2), 115-126.

[6] Cologni, A. L., Mazzoleni, M., & Previdi, F. (2016, June). *Modelling and identification of an electro-hydraulic actuator*. In 2016 12th IEEE International Conference on Control and Automation (ICCA) (pp. 335-340). IEEE.

[7] Yoon, J. I., Kwan, A. K., & Truong, D. Q. (2009, August). *A study on an energy saving electro-hydraulic excavator*. In 2009 ICCAS-SICE (pp. 3825-3830). IEEE.

[8] Tavakoli, R., Najafi, M., Tabesh, A., & Ashoori, T. (2017). *Comparison of Carbon Footprint of Trenchless and Open-Cut Methods for Underground Freight Transportation*. In Pipelines 2017 (pp. 45-55).

[9] Patnayak, S., Tannant, D. D., Parsons, I., Del Valle, V., & Wong, J. (2008). *Operator and dipper tooth influence on electric shovel performance during oil sands mining*. International Journal of Mining, Reclamation and Environment, 22(2), 120-145.

[10] Mirhaj, S. A., Kaarstad, E., & Aadnoy, B. S. (2016, January). *Torque and drag modelling; soft-string versus stiff-string models*. In SPE/IADC Middle East Drilling Technology Conference and Exhibition. Society of Petroleum Engineers.

[11] Teale, R. (1965, March). *The concept of specific energy in rock drilling*. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 2, No. 1, pp. 57-73). Pergamon.

[12] Dupriest, F. E., & Koederitz, W. L. (2005, January). *Maximizing drill rates with real-time surveillance of mechanical specific energy*. In SPE/IADC Drilling Conference. Society of Petroleum Engineers.

[13] Bourdon, J. C., Cooper, G. A., Curry, D. A., McCann, D., & Peltler, B. (1989). *Comparison of field and laboratory-simulated drill-off tests*. SPE drilling engineering, 4(04), 329-334.

[14] Pessier, R. C., & Fear, M. J. (1992, January). *Quantifying common drilling problems with mechanical specific energy and a bit-specific coefficient of sliding friction*. In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

[15] Chen, X., Gao, D., Guo, B., & Feng, Y. (2016). *Real-time optimization of drilling parameters based on mechanical specific energy for rotating drilling with positive displacement motor in the hard formation*. Journal of Natural Gas Science and Engineering, 35, 686-694.

[16] Orlandi, A. (1968). *I veicoli cingolati: descrizione del veicolo, elementi di meccanica delle terre nel sistema terreno-veicolo, il galleggiamento di un veicolo cingolato fuori strada, l'aderenza e lo sforzo di trazione, le resistenze al moto*. R. Pàtron.

[17] Wong, J. Y. (2008). *Theory of ground vehicles*. Wiley.

[18] Wong, Jo Yung. *Terramechanics and off-road vehicle engineering: terrain behaviour, off-road vehicle performance and design*. Butterworth-heinemann, 2009.

[19] Pugi, L., Galardi, E., Carcasci, C., Lucchesi, N. *Hardware-in-the-loop testing of bypass valve actuation system: Design and validation of a simplified real time model*, (2017) Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 231 (2), pp. 212-235. DOI: 10.1177/0954408915589513

[20] Pugi, L., Grasso, F., Pratesi, M., Cipriani, M., Bartolomei, A. , *Design and preliminary performance evaluation of a four wheeled vehicle with degraded adhesion conditions*, (2017) International Journal of Electric and Hybrid Vehicles, 9 (1), pp. 1-32. DOI: 10.1504/IJEHV.2017.082812

[21] Locorotondo, E., Pugi, L., Berzi, L., Pierini, M., Pretto, A. *Online State of Health Estimation of Lithium-Ion Batteries Based on Improved Ampere-Count Method* (2018) Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018, art. no. 8493825, . DOI: 10.1109/EEEIC.2018.8493825

[22] Locorotondo, E., Scavuzzo, S., Pugi, L., Ferraris, A., Berzi, L., Airale, A., Pierini, M., Carello, M. *Electrochemical Impedance Spectroscopy of Li-Ion battery on-board the Electric Vehicles based on Fast nonparametric identification method*, (2019) Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019, art. no. 8783625, DOI: 10.1109/EEEIC.2019.8783625

[23] Tashakori, S., Fakhar, M. *Suppression Of Torsional Vibrations In Drilling Systems By Using The Optimization-Based Adaptive Back-Stepping Controller* (2019) International Journal of Mechanics and Control, 20 (1), pp. 105-110.

[24] Liu Y F, Li J, Zhang Z M, Hu X H and Zhang W J 2015 Experimental comparison of five friction models on the same test-bed of the micro stick-slip motion system Mechanical Sciences 6 pp 15-28.

[25] Karnopp D 1985 *Computer simulation of stick-slip friction in mechanical dynamic systems* Journal of Dynamic Systems, Measurement, and Control 107(1) pp 100-103.

[26] Quinn D 2004 *A new regularization of Coulomb friction* J. of Vibration and Acoustics 126(3) pp 391-397.

[27] Dahl P R 1968 *A solid friction model* Tech. Report Tor-0158(3107-18)-1 Aerospace Corporation.

[28] Canudas de Wit C, Olsson H, Åström K J and Lischinsky P 1995 *A New Model for Control of Systems with Friction* IEEE Transactions on Automatic Control 40 pp 419-425.

[29] Borello L and Dalla Vedova M D L 2012 *A dry friction model and robust computational algorithm for reversible or irreversible motion transmissions* International Journal of Mechanics and Control 13(02) pp 37-48.

[30] Kikuuwe R, Takesue N, Sano ., Mochiyama H and Fujimoto H 2005 *Fixed-step friction simulation: from classical coulomb model to modern continuous models* International Conference on Intelligent Robots and Systems IEEE/RSJ 2005 pp 3910-3917.

ISSN 1590-8844
International Journal of Mechanics and Control, Vol. 22, No. 01, 2021

TEMPLATE FOR PREPARING PAPERS FOR PUBLISHING IN INTERNATIONAL JOURNAL OF MECHANICS AND CONTROL

Author1*   Author2**

* affiliation Author1

** affiliation Author2

ABSTRACT

This is a brief guide to prepare papers in a better style for publishing in International Journal of Mechanics and Control (JoMaC). It gives details of the preferred style in a template format to ease paper presentation. The abstract must be able to indicate the principal authors' contribution to the argument containing the chosen method and the obtained results. (max 200 words)

Keywords: keywords list (max 5 words)

1 TITLE OF SECTION (E.G. INTRODUCTION)

This sample article is to show you how to prepare papers in a standard style for publishing in International Journal of Mechanics and Control.

It offers you a template for paper layout, and describes points you should notice before you submit your papers.

2 PREPARATION OF PAPERS

2.1 SUBMISSION OF PAPERS

The papers should be submitted in the form of an electronic document, either in Microsoft Word format (Word'97 version or earlier).

In addition to the electronic version a hardcopy of the complete paper including diagrams with annotations must be supplied. The final format of the papers will be A4 page size with a two column layout. The text will be Times New Roman font size 10.

Contact author: author1[1], author2[2]

[1]Address of author1.
[2]Address of author2 if different from author1's address
E-mail: author1@univ1.com , author2@univ2.com

2.2 DETAILS OF PAPER LAYOUT

2.2.1 Style of Writing

The language is English and with UK/European spelling. The papers should be written in the third person. Related work conducted elsewhere may be criticised but not the individuals conducting the work. The paper should be comprehensible both to specialists in the appropriate field and to those with a general understanding of the subject.

Company names or advertising, direct or indirect, is not permitted and product names will only be included at the discretion of the editor. Abbreviations should be spelt out in full the first time they appear and their abbreviated form included in brackets immediately after. Words used in a special context should appear in inverted single quotation mark the first time they appear. Papers are accepted also on the basis that they may be edited for style and language.

2.2.2 Paper length

Paper length is free, but should normally not exceed 10000 words and twenty illustrations.

2.2.3 Diagrams and figures

Figures and Tables will either be entered in one column or two columns and should be 80 mm or 160 mm wide respectively. A minimum line width of 1 point is required at actual size. Captions and annotations should be in 10 point with the first letter only capitalised *at actual size* (see Figure 1 and Table VII).

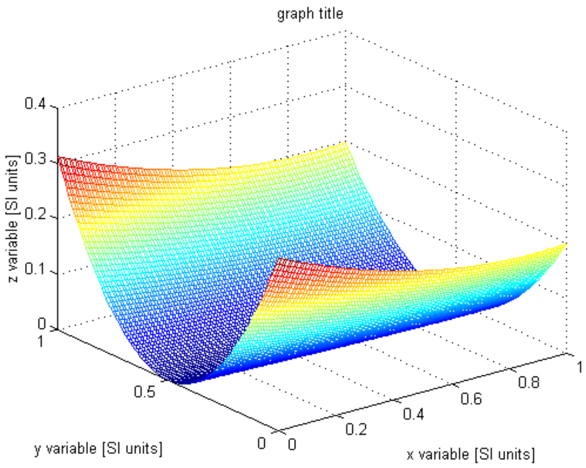


Figure 1 Simple chart.

Table VII - Experimental values

Robot Arm Velocity (rad/s)	Motor Torque (Nm)
0.123	10.123
1.456	20.234
2.789	30.345
3.012	40.456

2.2.4 Photographs and illustrations

Authors could wish to publish in full colour photographs and illustrations. Photographs and illustrations should be included in the electronic document and a copy of their original sent. Illustrations in full colour …

2.2.5 Equations

Each equation should occur on a new line with uniform spacing from adjacent text as indicated in this template. The equations, where they are referred to in the text, should be numbered sequentially and their identifier enclosed in parenthesis, right justified. The symbols, where referred to in the text, should be italicised.

- point 1
    - point 2
        - point 3

1. numbered point 1
    2. numbered point 2
        3. numbered point 3

$$W(d) = G(A_0, \sigma, d) = \frac{1}{T}\int_0^{+\infty} A_0 \cdot e^{-\frac{d^2}{2\sigma^2}} dt \qquad (1)$$

3 COPYRIGHT

Authors will be asked to sign a copyright transfer form prior to JoMaC publishing of their paper. Reproduction of any part of the publication is not allowed elsewhere without permission from JoMaC whose prior publication must be cited. The understanding is that they have been neither previously published nor submitted concurrently to any other publisher.

4 PEER REVIEW

Papers for publication in JoMaC will first undergo review by anonymous, impartial specialists in the appropriate field. Based on the comments of the referees the Editor will decide on acceptance, revision or rejection. The authors will be provided with copies of the reviewers' remarks to aid in revision and improvement where appropriate.

5 REFERENCES (DESCRIPTION)

The papers in the reference list must be cited in the text. In the text the citation should appear in square brackets [ ], as in, for example, "the red fox has been shown to jump the black cat [3] but not when...". In the Reference list the font should be Times New Roman with 10 point size. Author's first names should be terminated by a 'full stop'. The reference number should be enclosed in brackets.
The book titles should be in *italics*, followed by a 'full stop'. Proceedings or journal titles should be in *italics.* For instance:

REFERENCES (EXAMPLE)

[1] Smith J., Jones A.B. and Brown J., *The title of the book*. 1st edition, Publisher, 2001.

[2] Smith J., Jones A.B. and Brown J., The title of the paper. *Proc. of Conference Name*, where it took place, Vol. 1, paper number, pp. 1-11, 2001.

[3] Smith J., Jones A.B. and Brown J., The title of the paper. *Journal Name*, Vol. 1, No. 1, pp. 1-11, 2001.

[4] Smith J., Jones A.B. and Brown J., *Patent title*, U.S. Patent number, 2001.

International Journal of Mechanics and Control – JoMaC
Published by Levrotto&Bella

TRANSFER OF COPYRIGHT AGREEMENT

NOTE: Authors/copyright holders are asked to complete this form signing section A, B or C and mail it to the editor office with the manuscript or as soon afterwards as possible.	*Editorial Secretary address:* Andrea Manuello Bertetto Matteo D. L. Dalla Vedova, Lorenzo Pace *Dept. of Mechanical and Aerospace Engineering* *Politecnico di Torino* *C.so Duca degli Abruzzi, 24 – 10129 Torino – Italy* *e_mail: jomac@polito.it* *fax n.: +39.011.564.6999*

The article title:

By:____

To be Published in ***International Journal of Mechanics and Control JoMaC***
Official legal Turin court registration Number 5320 (5 May 2000) - reg. Tribunale di Torino N. 5390 del 5 maggio 2000

A Copyright to the above article is hereby transferred to the JoMaC, effective upon acceptance for publication. However the following rights are reserved by the author(s)/copyright holder(s):
1. All proprietary rights other than copyright, such as patent rights;
2. The right to use, free or charge, all or part of this article in future works of their own, such as books and lectures;
3. The right to reproduce the article for their own purposes provided the copies are not offered for sale.

To be signed below by all authors or, if signed by only one author on behalf of all co-authors, the statement A2 below must be signed.

A1. All authors:

SIGNATURE______________________________DATE__________ SIGNATURE______________________________DATE__________

PRINTED NAME____ PRINTED NAME____

SIGNATURE______________________________DATE__________ SIGNATURE______________________________DATE__________

PRINTED NAME____ PRINTED NAME____

A2. One author on behalf of all co-authors:
"I represent and warrant that I am authorised to execute this transfer of copyright on behalf of all the authors of the article referred to above"

PRINTED NAME____

SIGNATURE______________________________ TITLE______________________________ DATE______________

B. The above article was written as part of duties as an employee or otherwise as a work made for hire. As an authorised representative of the employer or other proprietor. I hereby transfer copyright to the above article to *International Journal of Mechanics and Control* effective upon publication. However, the following rights are reserved:
1. All proprietary rights other than copyright, such as patent rights;
2. The right to use, free or charge, all or part of this article in future works of their own, such as books and lectures;
3. The right to reproduce the article for their own purposes provided the copies are not offered for sale.

PRINTED NAME____

SIGNATURE______________________________ TITLE______________________________ DATE______________

C. I certify that the above article has been written in the course of employment by the United States Government so that no copyright exists, or by the United Kingdom Government (Crown Copyright), thus there is no transfer of copyright.

PRINTED NAME____

SIGNATURE______________________________ TITLE______________________________ DATE______________

CONTENTS – Special Issue "*Numerical modelling and simulation for systems engineering applications: novel methods in design, development, monitoring, diagnostics and prognos*tics"

CONTENTS – Regular Issue