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F GXGNQRO GP V'QH'C'O C'VGT'KN'E WVV'I 'O QF GN'HQT'J CRV'E"
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C"VJ GUK'UWDO K'VGF "VQ"
VJ GI TCF WCVG'UEJ QQN'QHP C'VWTCN'CP F 'CRRN'GF "UEK'PEGU"
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K' "R'CT'VKCN'HWNH'KNNO GP V'QH'VJ G'TGS WKTGO GP VU"
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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Görkem ÜNER

Signature :

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ABSTRACT

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F GXGNQRO GP V'QH'C'O C VGTICN'E WVVPI 'O QF GN'HQT'J CRVÆ"
TGP FGTÆ I 'CRRNÆC VIKP U"

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O UU'F gr ctvo gpv'qh'O gej cplecni'Gpi kpggtkpi "
Uwr gt xkuqt <Cuukv(Rtqh)F tOG0ij cp'Mqpwmngxgp"

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F gego dgt '4229.'343'r ci gu'

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J cr vë" f gxlegu" cpf "j cr vë" tgpfgtkpi "ku"cp"ko r qtvcpv'vqr kè"kp"vj g"dwti gqpkpi "hgrf"qh"
xktwcn'tgcrk\ "cr r ñecvqpu0k\ "vj ku"vj guku. "Kf guetkdg"vj g'f guki p"cpf "ko r ngo gpvcvqp"qh"
c"eww\pi "hqteg"o qf gn'kpvgi tcvkpi "c"j cr vë" f gxleg. "vj g"RJ CP VqO ."y kj "c"j ki j "ó"
r qy gtgf "eqo r wgt0O { 'i qcn'y cu'vq"dwkrf "c"ukz "f gi tgg" ó"qh'ó"htggf qo "hqteg"o qf gn'vq"
cmqy "wugt"vq" kpvgtcev'y kj "vj tgg"ó" f ko gpukqpcn'f ghqto cdng" qdlgeu0"O gvj qf u" hqt"
j cr vë" tgpfgtkpi " kpenv\kpi " i tcr j lecn' tgpfgtkpi ." eqmkukqp" f gvgevkqp" cpf " hqteg"
hggf dcem'ctg" kmwutcvgf ." ko r ngo gpvcvqp"qh'j cr vë" tgpfgtkpi "u{ uvgó "ku" kvtqf weg. "
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Mg{y qtf u<Xktwcn'Tgcrk\ ."J cr vë. '8F QHJ cr vë" Tgpfgtkpi ."Eww\pi "Hqteg"O qf gn'

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J CRVÆ"W I WNCOCNCTK'¥ P'D T'O CN\ GO G'MGUO G'O QFGN P P "
I GN V T NO GU "

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[Ænugn'Nucpu.'O cnkpg'O Æj gpf kurk k'D¾nAo Æ"
Vgl 'I ¾pgvkekuk<[ctf OF q±OF tOG0nj cp'Mqpwmugxgp"

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Ctcn,m4229.'343"uc{hc"

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J cr vÆ'ekj c| rct'xg'j cr vÆ'ucj pgrgo g'ucpcn'f gt±gmkn'w{i wncocnct,pf c'i grk o gmg'qmp"
¾pgo rk' dkt" mupwf wt0' Dw" vgl f g." j cr vÆ' ekj c| ,p." RJ CP VqO ." { Ænugn' i Æ±nÄ" dkt"
dkri kuc {ct "kg"vAo ng{kek'dk"nguo g"mwxgv'o qf grkpk"vcuct,o ,"xg"i gt±gmg vto gukpk"
vp,o rcf,o 0'J gf ghko "mwrp,e,p,p" Æ±"dq{www'f ghqto g"qrddkt"qdlgrgrg"gnkkg ko "
uc rco cu,pc" k kp"xgtgp"8"ugtdgvrkn'f gtgegrk'mwxgv'o qf grkpk'qmw wto cm,0'J cr vÆ"
ucj pgrgo g."i tchkn'ucj pgrgo g."±ctr , o c"cn' ,rco cu,"xg"mwxgv'i gt'kdgungo g"o gvqrct,"
i ¾vgtkfk" j cr vÆ" ucj pgrgo g" ukvgo kpk" i gt±gmg vtko guk' uwpwf w." xg" w{i wncocn"
ukvgo kp'i g±gtrrk k'nupvtqn'gvo gnlekp"fg gtrgpf ktkf k0""

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Cpcj wt'Mgnko grgt<Ucpcn'I gt±gmkn"öJ cr vÆö'Ekj c| ,.'8'Ugtdgvrkn'F gtgegrk'J cr vÆ"
Ucj pgrgo g.'Mguo g'Mwxgv'O qf grk'

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To My Family

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ACKNOWLEDGMENTS

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P qvj kpi "ku'gxgt'f qpg'cmppg=vj wu'ky qwf 'hng'v'vj cpm'egt v'k'p'r gqr ng'y j q'j gr gr gf "o g"
cmppi "vj g'y c{ 'y kj 'vj ku'r tqlgex0'

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Kco "gzvgo gr{ "i tcvghw'ht'vj g'uw r qt v'cpf 'i wk' cpeg'qh'o { "uw r gtxluqt.'Cuukw0Rtql0'
F t0'GO'ij cp'Mqpwmngxp.'y j q.'Khgn'y cu'tgur qpukdng'ht'cf xcpeki "o { "npqy rgi g"
kp'vj g'ctgc'qh'XkwcnT gcrk{ 0"

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O cp{ "vj cpm"i q"vq" Cpcu"Cdkf k'y j q"j gr gr gf "o g"vq" dgwgt" wpf gtucpf "j cr v'e" cpf "
i tcr j le'tgpf g'kpi "cni qtkj o u'cpf 'y j q'cuukv'gf "o g'kp'f gxgr kpi "vj g'un'ku'p'ggf gf "vq"
d'w'kf "eqo r r'gz"E- - "cte j k'gewt g0'Wo w'Mq±cm'i cxg"o g"lf gcu"qp"j qy "vq"uq'kg"vj g"
j cr v'e'tgpf g'kpi 'r tqdrgo u'cpf 'r v'k'p'w' { 'cpuy gtgf "d{ 'E- - 's w'guk'p'u0'

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Kqy g'o cp{ "vj cpm'vq"o { "ht'k'p'f u'y j q'u'w'f { "kp'vj g'O GVWO ge j cvt'q'pleu'Ncdqtcvqt { "
hqt "vj g'k'r t'gek'q'wu'uw r qt v'cpf 'r t'gugpeg0'

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Ncu"vj cpm"i q"vq"o { "hco kn{."y j q"t'ckugf "o g"y gm'cpf "i cxg"o g"n'qu'qh"j gr "cpf "
uw r qt v0'

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NOMENCLATURE

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DOF	F gi tgg'ó'qh'ó'htggf qo "
F	Hqteg"
k	Ur t kpi "Ukhtp guu'E qghhlekpv"
b	F co r kpi 'Eqghhlekpv"
v	Vtcpu r v kpcn'X g m e k v { "
Δx	F k u r m e g o g p v'
DC	F k g e v' E w t t g p v'
$RGBA$	T g f . ' I t g g p . ' D m w g . ' C m j c "
CT	E q o r w g t k g f " \ q o q i t e r j { "
MRI	O c i p g v k e ' t g u q p c p e g ' k o c i g t "
$2D$	V y q ' F k o g p u k a p c n i'
$3D$	V j t g g ' F k o g p u k a p c n i'
S	U w t h c e g ' q h ' q d l g e v'
P	C p " c t d k t c t { ' m e c v k p "
f	H w p e v k p "
n	U w t h c e g ' p q t o c n i'
Δf	I t c f l g p v ' q h ' y j g ' h w p v k p "
$AABB$	C z k u ' C r k i p g f ' D q w p f k p i ' D q z "
OBB	Q t l e p v g f ' D q w p f k p i ' D q z "
T	V q t s w g "
C_0, C_1, C_2	E q g h h l e k p v u ' q h " u g e q p f ' q t f g t ' r q n f p q o k c n i'
AP	X g e v q t ' h t q o " e a q t f k p c v g u ' q h ' u v f n w u ' v k r ' r q k p v ' v ' e a p v c e v ' r q k p v'
P_{ijk}	V j g ' e a p v t q n i r q k p w "
$B_i(x), B_j(y), B_k(z)$	5 " f g i t g g ' D g t p u v g k p ' r q n f p q o k c n i ' q t ' D g l k g t ' d c u k u ' h w p e v k a p u'
Q	R q u k v k a p ' q h ' y j g ' q d l g e v'
ΔQ	E j c p i g u ' k p ' r q u k v k a p ' q h ' y j g ' q d l g e v'
ΔP	E j c p i g u ' k p ' r q u k v k a p ' q h ' y j g ' e a p v t q n i r q k p w "
Q_{new}	V j g ' f g h q t o g f ' r q u k v k a p u ' q h ' y j g ' x k t w c n i ' q d l g e v'
a	c e e g r t c v k p p "

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<i>u</i>	P qf cn'F kur rnego gpv"
<i>i</i>	kj "pqf g"
<i>J</i>	Iceqdkcp"
<i>K</i>	Ukhhpguu'O cvtkz"
<i>U</i>	F kur rnego gpv'O cvtkz"
<i>N</i>	P wo dgt"qh'vj g"P qf gu"
<i>w</i>	Tqvcvkqpcn'Xgmekv "
μ	Hlevkqpcn'Eqghlekcpv"
<i>M</i>	F co r kpi 'O cvtkz"
<i>L</i>	Ngpi vj "qh'vj g'eqpvcev'ctgc"
<i>H</i>	F gr vj "qh'vj g'eqpvcev'ctgc"
<i>E</i>	[qwpi 'O qf wwu"
<i>R</i>	Tcf kwu'qh'vj g'vqpn'vr "
<i>CATIATM</i>	Eqo r wgt/Ckf gf "Vj tgg/F ko gpukqpcn'kpvtcev'kg'Cr r necvkqp"
<i>OpenGLTM</i>	Qr gp'I tcr j leu'Nkdtct {"
<i>F_{cutting}</i>	Ewwkpi "Hqteg"
<i>F_{res}</i>	Tgukucpeg'Hqteg"
<i>F_f</i>	Hlevkqp'Hqteg"
<i>T_{cutting}</i>	Ewwkpi "Vqts wg"
<i>F_{gravity}</i>	I tcxkv "Hqteg"
<i>T_{pitch}</i>	Vj g'vqts wg'qh'r kej "
<i>T_{yaw}</i>	Vj g'vqts wg'qh'cy "
<i>T_{roll}</i>	Vj g'vqts wg'qh'tqmi"
<i>K_p</i>	Wpk'Rqy gt'Eqpuwo r vkqp"
<i>VR</i>	O cvgtkcn'Tgo qxgf 'kp'c'r gtkqf "qh'E {eng"
<i>HDAPI</i>	J cr vke'F gxleg'CRK
<i>HLAPI</i>	J cr vke'Nkdtct {"CRK
<i>OBJ</i>	Y cxghtqpv'I tcr j le'Hqto cv"
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CHAPTER 1"

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INTRODUCTION

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Vj g"j cr v'e'f gxlegu'cpf "j cr v'e'v'ej pqm{ { "j cxg'dgeqo g'c'uki p'k'lecpv'kuwg'lp'xkt wcn' tgerkv{ "lp'tgegpv' { gctu'0C"j cr v'e'f gxleg'i gu'wugt"o qv'qp"cpf "i k'gu'wugt" c"ugpug"qh' v'wej "y kj "eqo r wgt"i gpgtcv'gf "xkt wcn'gp'xktqpo gp'u."uq"v'j cv'y j gp"xkt wcn'qdlgeu" ctg"v'wej gf." v'j g{ "uggo "tgcni'cpf "v'pi k'ng'0F w'g"v'j ku"ko r qt'v'p'v' ecr cdk'kv{." v'j g" cr r' r'ecv'k'pu" f gx'ng'r gf " d{ "j cr v'e'f gxlegu"j cxg" d'ggp" wugf " kp" ugx'g'tcn' k'pf w'ut'kgu" k'pen'f k'pi " cw'qo q'v'x'g." eq'ph'ge'v'k'p'ct{." x'kf'gq" k'pf w'ut{." h'q'vy gct." x'kf'gq" i co gu." lgy grt{." o q'ngew'rt" o q'f gr'k'pi ." ur qt'v'k'pi " i q'q'f u" cpf " g'v'e'0 J cr v'e'v'ej pqm{ { " cnuq" ko r ceu" v'j g" o g'f le'cn' h'gr'f " cpf " j cr v'e' k'p'v'gi tcv'gf " uko w'rc'v'k'pu" v'cm'g" v'j g" er'cu'le'cn' o g'v'j q'f u'r' r'eg'v'k'p'o g'f le'cn'h'gr'f 0""

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K'ku'cp" k'p'v'gt'g'v'k'pi " cr r' r'ecv'k'p"v'j h'qto " u'j cr g"kp" c" xkt wcn' tgerkv{ " gp'xktqpo gp'v'0 E'w'w'k'pi "ku'cp"gu'ug'p'v'k'n'q'r g'tc'v'k'p'k'p"u'j cr g'h'qto k'pi "v'cun'ic'pf "u'qo g'v'j cr gu'q'h'qdlgeu" o c{ "dg'v'j q'w'j v'v'q'dg'h'qto gf "cu'v'j g't'gu'w'v'q'h'e'w'w'k'pi 0K'ku'hp'qy p'v'j cv' uko w'rc'v'k'p'q'h' e'w'w'k'pi " q'r g'tc'v'k'pu" y kn' r' r'ec{ " cp" ko r qt'v'p'v' t'q'rg" kp" xkt wcn' tgerkv{ " y kj " v'j g" ko r r'go gp'v'k'p'q'h'j cr v'e'f gxlegu'0

"

K'p" k'pf w'ut'k'cn' cpf " o g'ej c'p'le'cn' f g'v'ki p" h'gr'f u." v'j g'tg" ctg" dt'q'cf " ct'geu" q'h' r q'v'g'p'v'k'n' t'gug'ct'ej "k'p'v'q" f k'h'g't'g'p'v'e'w'w'k'pi " cr r' r'ecv'k'p'u" r'k'ng"v'j t'gg" f ko gp'uk'q'p'cn'eqo r wgt" c'k'f gf " f g'v'ki p" *ECF + "eqo r wgt" c'k'f gf " o c'p'w'k'ce'w'v'k'pi " *ECO + " cpf " t'cr k'f " r t'q'v'v'f r k'pi 0V'j g" f g'v'ki p'g'tu" wugf " er'c{ " o c'v'gt'k'cn' q't " t'g'cn' o c'v'gt'k'cn' h'q't " q'f " f g'v'ki p" cr r' r'ecv'k'p'u'0 Y kj " p'gy "v'ej pqm{ k'gu." ECF "cpf "ECO "v'q'q'n'ct'g" wugf "h'q't "dg'w'gt" cpf " h'cu'v'gt" f g'v'ki p'u'0 P'q'p'g" q'h'v'j g'ug'eqo r wgt" d'cu'gf "v'q'q'n'c'x'k'c'k'rd'ng"j cxg'c'm'qy gf " f g'v'ki p'g'tu"v'q'r j { u'k'ecm{ "i g'v'k'p" v'wej "y kj "v'j g" f g'v'ki p"y j k'ng"y q't'n'k'pi "q'p" c"eqo r wgt'0D{ "v'j g" c'f cr v'c'v'k'p'q'h'j cr v'e'v'ej pqm{ { " cnuq" ko r ceu" v'j g" o g'f le'cn' h'gr'f " cpf " j cr v'e' k'p'v'gi tcv'gf " uko w'rc'v'k'pu" v'cm'g" v'j g" er'cu'le'cn' o g'v'j q'f u'r' r'eg'v'k'p'o g'f le'cn'h'gr'f 0""

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vgej pqrni { " vq" vj gug" eqo r wgt" ckl gf " vqnu." vj g" wugtu" j cxg" dgwgt" eqpvtqrn' cpf "
hgzklrkv\ "y j lej "ecppqv'dg'cej kxgf "d{ "vj gug'eqo r wgt"dcugf "vqnu0"

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Ewwkpi "ku"cnuq" cp" ko r qtvcpv'qr gtcvqp" kp"o cp{ "o gf lecn'hgrf u0' k0"o gf lecn' cpf "
f gpvni'hgrf u="engcpkpi "f gec{ "qh"vgyj . "i tkpf kpi "qh"vgyj "cpf "dqpgu."tguj cr kpi "vgyj "
cpf " dqpgu." cpf " f tkni' j qrgu" hqt" ko r ncpw" ctg" f qpg" d{ " ewwkpi " qr gtcvqp0' Vj g"
cr r tgpvkguj kr "o qf gnu'hqt"vj gug"qr gtcvqpu="htuv'ugg."vj gp"fq."cpf "vj gp"vgej "j cxg"
dggp"o quvf "wugf "cu'c'tcf kkpncn'o gjv qf "hqt"vj g'tcckpki "qh'vj g'o gf lecn'uwf gpw0"

"

Vj g" uko wrcvqp" qh' ewwkpi " qr gtcvqp" dcugf " u{ uvgo u" kpvgi tcvf " y kj " j cr v"e"
vgej pqrni { "j cu'dgeqo g"guugpvkn'kp"vj g"o gf lecn'hgrf 0'D{ "vj g"cf cr vcvqp"qh'j cr v"e"
f gxlegu" kp" xktwcn'tgcrk\ " cr r nccvqpu." vj g" wugtu" j cxg" r tqxkf gf " xctkqu" hgcwtgu"
y j lej "ecppqv'dg'cej kxgf "d{ "em'uulecn'vgej pls wgu0"

"

Rrcvke"o qf gnu"ctg" wugf "hqt" tckpki "kp"o quv"o gf lecn'ctgcu0' k0" f gpvni'cpf " qvj gt"
o gf lecn'tcckpki "ctvkecn'vgyj "cpf "dqpgu"o qf gnu"ctg" wugf "y j lej "ecppqv" r tqxkf g"
vj g"rgxgn'qh'tgcrkuo 0Ukpeg"vj gug'ctvkecn'o qf gnu"ctg"pqv'equ'ghge'vkg0'Vj g'wug'qh"
tgo qxgf "vgyj "qt"dqpgu"o ggu"vj g'tgcrk\ "tgs wktgo gpv'paxgtvj grguu"ku"s wcpv\ "ku"
pqv'gpqi j 0J qy gxgt'xktwcn'tgcrk\ "cr r nccvqpu'r tqxkf g'pqv'qpn\ "f khtgtpv'o cvgtkn'
r tqrgt'vku"cpf "rgxgn'qh'f gvku"dw'cnuq"ugxgcn'uegpctkqu"cpf "ecugu"y j lej "ecp"dg"
hceg' "vj tqwi j 'tgcni'k0'

"

Vj g"clo "qh'ewwkpi "qr gtcvqp"ku"vq"tgo qxg"cur gtkkqu"qp"vj g"uwtrceg"qh'vj g"kggo "
rtqeguugf "d{ "vqnu"qt"o cej kpgt { 0Ewwkpi "qr gtcvqp"j cu'vy q"o ckp"ukf gu<hqtg"cpf "
i gqo gvt { 0' K'ku" uckf " vj cv' r gqr rg" j cu'f khlwvku" kp" ectt { kpi "qw" r tgekukp"y qtni'
y kj qw'hqtg'hggf dcn0'Vj g'i gqo gvtke'ukf g'ko r rku'vj cv'vj g'qdlgevu'wvf gt"cpf "chgt"
vj g'ewwkpi "qr gtcvqp"ej cpi g'vj gk"uj cr gu0Ukpeg" ewwkpi "ku'cp"qr gtcvqp"vj cv' mecm\ "
f ghqto u"vj g'qdlgev."r j { ulecn'uko wrcvqp"qp"vj g"r j gpqo gpqp"ku"vq"eqo r nccv\ "vq"
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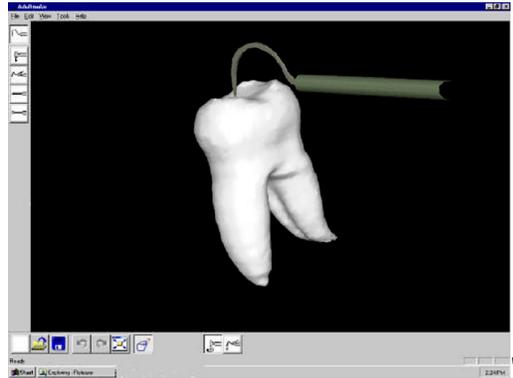
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"

f ghqto cdrng"qdlgev'd{ "r tqdlkpi "cpf "vj gp"r j { ukecm{ "f ghqto "vj g"qdlgev'd{ "f khtgtpv"
ewwkpj "vqqu"j gcf "uj cr gu"uk gu"cpf "tqvcvkp"ur ggf u"kp"tgcni'vko g"y kj "vj ku"ewwkpj "
o qf gr0'Vj g"cr r nekcvkp"kpemf gu"dqj "5F "i tcr j kecn'f ghqto cvkqp"cpf "8F QH"j cr vke"
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1.1 SURVEY OF LITERATURE

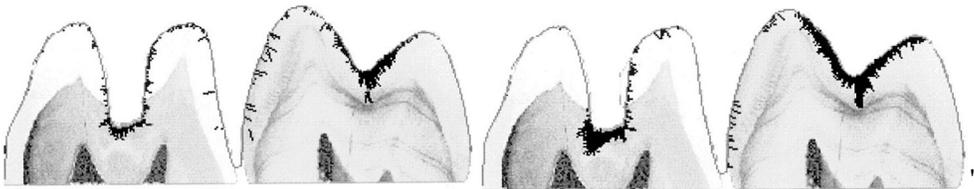
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Vj g{ 'uj qy gf "vj cvj cr vke"o"dcugf "f gxlkgu'ctg'ecr cdrng'qh'r tqxkf kpi "vj g'xk wcnit'gcnk{ "qh'f gpvcni"
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"
"



Hki wtg"30" Hktu'Xk wcnit'gcnk{ "F gpvcni'vcklpi "U{ ugo "Uetggp"]86_""

Vj qo cu'gv'cr0'f gxgnr gf "c"vcklpi "u{ ugo "y j lej "gpvcni'qr gtcvkq "vq"r tcevkq"vj g"
f gvevkq"qh'ectkwa"ngukpu"]: 2_0'Vj gk "f go qpucvkq"dcugf "qp"r tqdlkpi "vj g"uwthceg"
qh'vj g"vqqj . 'dw'vj gk "u{ ugo "ku'pqv'eqpukf gtlpi "ewwkpj "qr gtcvkqp0'
"

Kp" Hki wtg" 304. "kmwucvkq"qh'vj g" hqtegu" cr r nkgf "d{ "vj g" f gxlkg" f wtkpi "c" f gpvcni'qr
r tqdlkpi "hqt" f gpvcni'ectkwa"ku"uj qy p0'Vj g" dnem'tgi kqpu"ctg" xgevtu" f guetkdkpi "vj g"
f kgevkq"qh'vj g"gzgtvgf "hqteg0'Vj g"ngpi vj "qh'vj g" xgevtu"ku'r tqr qt'vcklpi"vq"vj g" hqteg"
gzgtvgf 0'Vj g'vr "qh'vj g" xgevt "kpf kecvu'vj g" mecvkq"cv'y j lej "vj g" hqteg'y cu'r tgu'pvgf 0'
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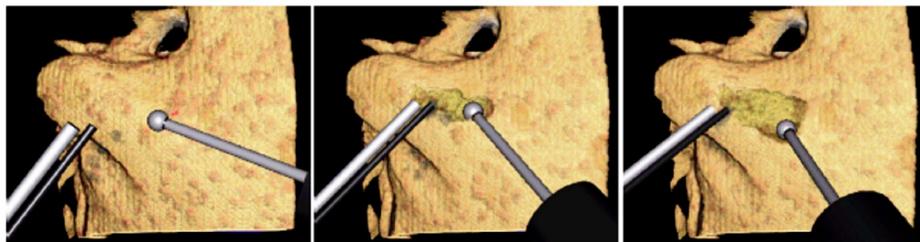


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"
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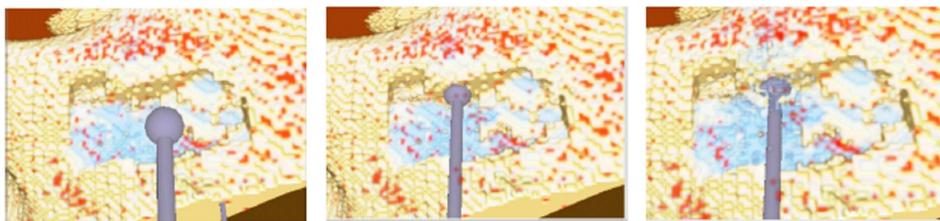
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ewwkp{ "qr gtevekp"]3_]4_0Vj g{ "ej ctcevegtk gf "vj g'tgi kqpu"qh'dqpg"cpf "vj g{ "guvko cvgf "
grvukle"htegu"y kj kp"vj g"dqpg"d{ "wukpi "cp"kf gcrk gf "ur j gtg"vj cv'ku"tgr tguvkvpi "vj g"
dwt"vr 0'D{ "wukpi "gzi gtlo gpvni'f cvc."cp"gzr gtlo gpvni'u{ uvgu "y cu'ugv"wr "vj g"hk'vj g"
o qf grlqh'dqpg"dwtlpi 0'

"
"



Hki wtg'305" C"xktwcnrdwtlpi "ugs wvpegu'r gthqto gf "kp"vj g'o cuvkl' tgi kqp"
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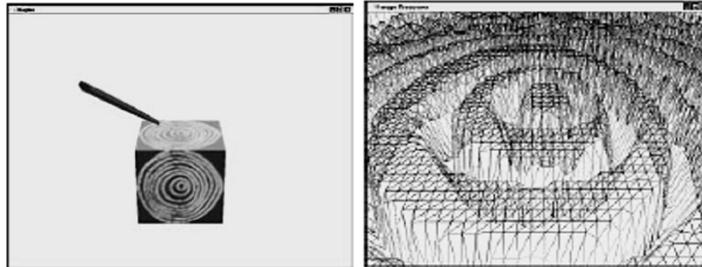


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"
"
"

C0' Derklgr cnk' cpf " V0' Mguexcf cu" f gxgrgr gf " c" hqteg" eqo r wcvkqp" o gj qf " qh'
o gej cplecr'0 cej kpkpi 'dcugf "qp'yj g'r tkpek r g'qh'ur tkpi 'hqt'yj g'r cyj 'r rppkpi 'qh'tqdq0'
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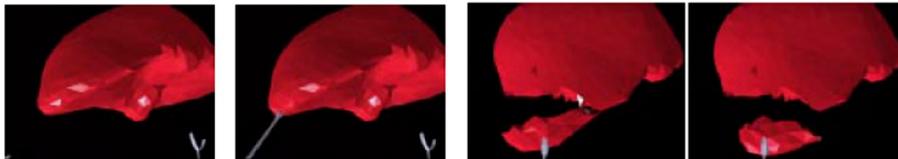


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"
"

J gtx² "F grkpi gwg"gv'cn0'r tqr qugf "c"övgpuqt"ó"o cuuö"hqteg"o qf gr'uko krc"vq"yj g'y gr'
mpqy p" öur tkpi " ó" o cuuö" o qf gr']42_0' Vj g{" uko wrcvg" ewvkpi " d{" grko kpcvkqp"
övgtcj gf tcn'rgo gpwö'htqo 'yj g'o qf gr0"

"
"



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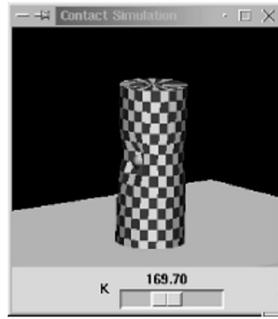
O qj ugp"O cj xcuj " cpf " Xkpegpv'J c{y ctf " r tguqpvgf " c" r tg/ecr wcvkqp" o gj qf " hqt"
j cr vke"uko wcvkqp"qh'eqpvcevdgwy ggp"cvqqr'cpf "c"pqprkpgct"fg hqto cdr g"o qf gr']6; _"
cpf "c"htcewtg"o gej cpleu'crr tqcej 'hqt'uj ctr 'kpwgtcevkqp0]69_]6: _"

"

Vj ku'r tg/ecr wcvkqp"o gj qf "y cu'dcugf "qp'yj g"dqqmnggr kpi "qh'hqteg"fg hgevkqp"ewtxgu"
uqtf g" cv'yj g"pqf gu"qh'öc"tkpi wrcvg" dqf {"ö"uwthceg0'Vj ku"o gj qf "ku"ghgevkxg" hqt"
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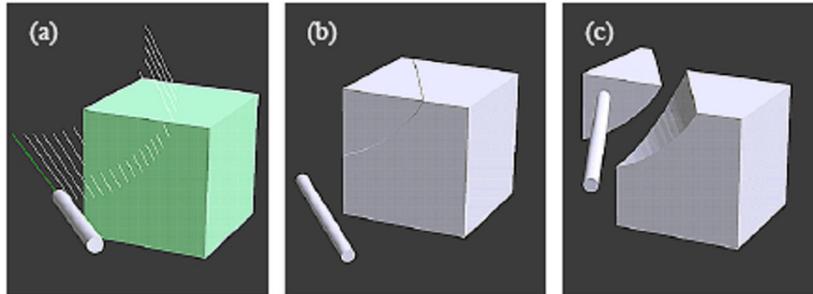
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Vpcnc"gv'crl'eqpukf gt "yj g'ewwki "hqtg'vq'dg'c"htkvwqp'hqtg'dgy ggp'yj g'vqnl'cpf "yj g"
tki kf "dqf { 'y j lej 'ku'eqo r wgf "d{ 'yj g'xgmekv{]9; _0'

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Hi wtg"30" C"u{ungo "yj cv'uj qy u'xktwcn'ewwki 'r tqeguu"]9; _"

"
"

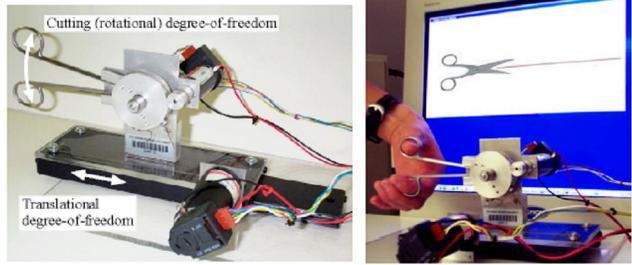
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cu" c" ur tkpi "hqtg" r tqr qt'vqpcn' vq" kpf gpv'vwqp" f gr vj " crqpi " uwt'ceg" pqto cn' cpf " c"
f co r lpi "hqtg"r tqr qt'vqpcn'vq"v'cpi gpv'cn'xgmekv{]: _0'

"

C00 0Qmco wtc'gv'crl'eqo r wgf "yj g'ewwki " hqtg'lp"yj g'uko wrcvqp'qh'j cr vle'uekuqtu"
dcugf "qp"yj g'hw'pf co gpv'cn'r tkpek'rg'qh'ur tkpi "]82_0Vj g{ 'ej qug'vj g'tqvc'vqpcn'cpi ng'qh"
yj g'uekuqtu'cu'vj g"xctkcdrg"vq'eqo r wgf "yj g'ewwki "hqtg'0Vj ku'o gyj qf "ku'gh'ge'v'xg'hqt"
yj g'uko wrcvqp'qh'ewwki "gr'c'vle"qdl'ge'0"

"

"



Hki wtg'30 " 4F QHj cr vle'uekuqtu'cpf 'i tcr j le'f kur r:{ 'u{vgo "]82_'"

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"

I wcp{ cpi "Nkw" gv' cr0' f gxgr "ewwkp "hqtg" o qf gr' dcugf " gZr gtlc gpvcn' f cvc0' Vj g{ " y qtnf " qp" cp" gZr gtlc gpvcn' u{vgo " v" f vgtc kpg" vj g" f co r kpi " o cvtk" cpf " f gpvcn' r ctco vgtu' u{vgo qh'v' g' vggj . "vqrv{ r g'vge0']4: _0"

"

"



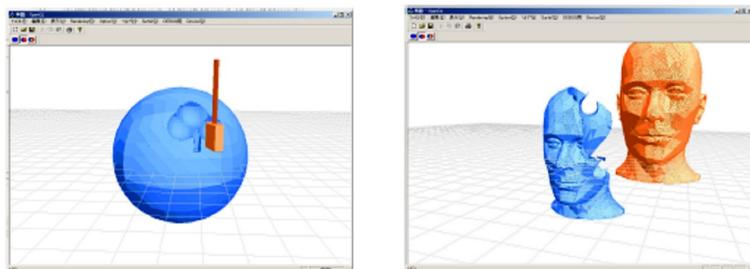
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"

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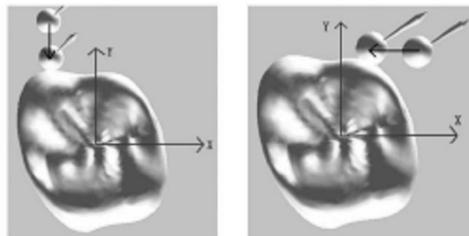
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"

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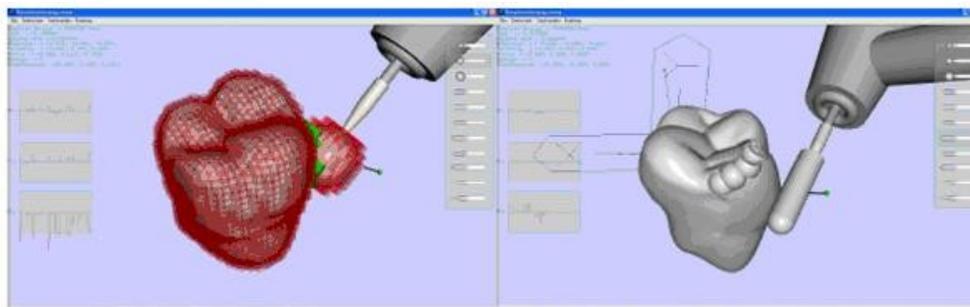
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"

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"

:

Vj g" j cr vle" f gxleg" r tqxkf gu" j ki j " hf grkx{ " uko wævkp" qh" vj g" ðGzr nqtgtö." ðF tknö."
 ðEcttkgtö."ðVco r gt"cpf "Ectxgt"vqmqö."gpcdrkpi "c"uwf gpv"vq"r tcevek"r tqegf wtgu"y kj "
 eqphkf gpeg."cpf "c"vgej gt "vq"s wcpvkh{ "c"uwf gpv"vq"ghhqt u0'K'qhhtu"vj g"qr r qtwpkv{ "vq"
 r tcevek" r tqegf wtgu" cu" qhvq" cu" pggf gf ." y kj " pq" cf f kkvpcn' equv' hqt" o cvgtkcn0'
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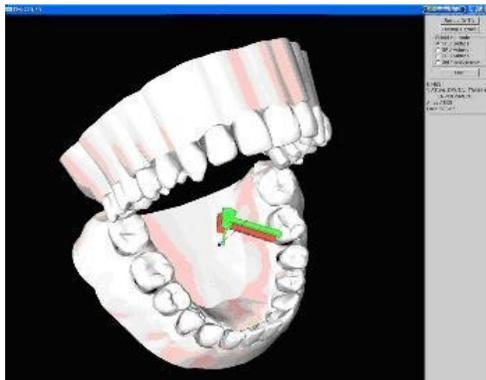


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"

Mqpwmugxgp" gv'cn0'f gxgnqr gf "c" f gpvcrn'vcklpi "u{ uogo "vj cv'wugu" j cr vle" f gxleg" hqt"
 tgrkx{ "qh"vj g"cr r nkvkqp0'Vj g{ "wugf"r tqz { "ó"dcugf "ur tkpi "f co r gt"u{ uogo "hqt" j cr vle"
 hqtg'tgpf gt kpi "wukpi "vj g'Qr gpJ cr vleu'CRKku'qy p'hqtg'o qf gr0'Vj g{ "cnq"ko r ngo gpv"
 c"xkdtcvkqp'r ctco gygt'hqt'tgcrkuo "qh"vj g"u{ uogo 0]62c_"

"
 "



Hki wtg'307" O GVW'Xktwcn'Tgcrkx{ 'F gpvcrn'Vtcklpi "U{ uogo]62c_"

"

;

1.2 OBJECTIVES OF THE THESIS

"

Vj g" qdlgevkxg" qh" vj ku" vj guku" ku" vq" f gxgnr " c" ewwki " o qf gr' hqt" j cr v" tgpf gtlpi "

cr r rncvku0Vj g'dcuke'hwpevku0'vj cv'ctg'clo gf "ctg<

"

- Vq'I gpgtcvg"J cr v" Ewwki "Hqteg"O qf gr'
- Vq'F gxgnr "c"J cr v" Cr r rncvku0'hqt' Ewwki "Qr gtcvku0"
 - Vq'I gv'ho kkt'y kj "J cr v" Vgej pqm { "
 - Vq'kpxguki cvg"J cr v" Tgpf gtlpi "('F ghqto cdrq"Qdlgev'O qf gnu"

"

Vj g" uqhy ctg" ku" f guki pgf " cpf " f gxgnr gf " eqpukf gtlpi " vj g" cf f kku0" qh" qv gt "

r ctco gygtu" vj cv' ghgeu" ewwki " qr gtcvku0' Cnu" uqhy ctg" ku" c" vgo r rncv" hqt" j cr v" "

cr r rncvku0'hqt' ewwki " qr gtcvku0'cpf " i gpgtcnr tqr qugu0'

"

1.3 THESIS OUTLINE

"

Vj g" 4^{pf} " ej cr vgt" ku" cp" kvqf veku0" vq" j cr v" vgej pqm { " cpf " j cr v" kvgt hcegu0'

F ghku0'cdqw" j cr v" f gxlegu" cpf " j cr v" kvgt hcegu" y km'dg" i kxgp0'Vj g" 5^{tf} " ej cr vgt "

tgxky u" vj g" j cr v" tgpf gtlpi " uelgpeg. " kvnwf lpi " i tcr j kcrn' tgpf gtlpi " cpf " eqmku0' "

f gvgeku0' Vj g" 6^{ij} " ej cr vgt " f guetkdu" vj g" o quv' ko r qtvcv' r ctv' qh' j cr v" tgpf gtlpi =

j cr v" hqteg" tgpf gtlpi 0' Vj g" 7^{ij} " ej cr vgt " gzr rku0' qwt" j cr v" ewwki " o qf gr' Vj g" 8^{ij} "

ej cr vgt " kmwutcvgu" vj g" f guki p" cpf " vj g" ko r ngo gpvku0' qh' ewwki " hqteg" o qf gr' vq" cp "

cr r rncvku0' Vj g" 9^{ij} " ej cr vgt " eqpenf gu" vj ku" vj guku" d { " uwo o ctkt lpi " vj g" y qtm' cpf "

f kuewulpi " hwwt g" f ktgeku0' Nkgtcwt g" uwt xg { u" hqt " gcej " ej cr vgt " ctg" i kxgp " kp" gcej "

ej cr vgt 0'

"

J cr vĕ" f gxlegu" j cxg" xct { lpi " eqo r ngzkkgu." cpf " ecp" o qxg" kp" f kHgtgpv" f ktgevkpu0
 Hqteg" hggf dcmi" f gxlegu" ctg" qhngp" f guetkldg" d { "vj gk" ðF gi tggg" qh" Hggf qo ð. "ðF QHð0
 C" ðF gi tgg" qh" Hggf qo ð" tghgtu" vq" c" f ktgevkqp" qh" o qxgo gpv0 Eqo o qp" F gi tggg" qh"
 Hggf qo " lpenwf g" vj g" vtcpurvkqp" kp" Z" czku" ðtki j v/ rghv" o qxgo gpv0. "vj g" vtcpurvkqp" kp" [" "
 czku" ðwr / f qy p" o qxgo gpv0. "vj g" vtcpurvkqp" kp" \ " czku" ðkp/ qw" o qxgo gpv0" cpf " " tqm"
 ðtqvcvkqp" cdqw" vj g" \ " czku0. " rkej " ðtqvcvkqp" cdqw" vj g" Z" czku0. " cpf " { cy " ðtqvcvkqp"
 cdqw" vj g" [" czku00" kp" Hki vtg" 4B. "vj g" o cetq" o qxgo gpv" cpf " o letq" o qxgo gpv" qh" c"
 rj cpvqo " v{ r g" j cr vĕ" f gxleg" uj qy p0"

"
 "



c+O cetq" o qxgo gpv0 Uj qy lpi " b qxgo gpv" qh" vj g" d+O letq" o qxgo gpv0 Uj qy lpi " o qxgo gpv" cv" vj g"
 RJ CP VQO " Qo pkcto " cpf " vj g" dqf { 0 uv{ nnu0

Hki vtg" 4B" O cetq" cpf " O letq" O qxgo gpv" qh" Rj cpvqo " v{ r g" j cr vĕ" Fgxleg"

"
 "

F gi tggg" qh" Hggf qo " ecp" tghgt" dqj " vq" j qy " c" f gxleg" nggr u" vtcem' qh' r qukkqp. " cpf " j qy " "
 c" f gxleg" qwr wu" hqtegu" Hqt" gzco r ng. " c" o qwug" ku" c" 4" F QH" kpr w" f gxleg" y j lej " kv"
 nggr u" vtcem' qh' r qukkqp" kp" vj g" tki j v/ rghv" F gi tgg" qh" Hggf qo . " cpf " vj g" hqty ctf /
 dceny ctf " F gi tgg" qh" Hggf qo 0C" lq { u vlen' ku" cnuq" c" 4" F QH" f gxleg. " dw' ku" F gi tggg" qh"
 Hggf qo " ctg" f kHgtgpv0 Lq { u vlen' tqvcvgu" hqty ctf u dceny ctf . " cpf " tki j v/ rghv0 C" hqteg"
 hggf dcmi" lq { u vlen' ku" c" 4" F QH" f gxleg" y kj " hqteg" hggf dcmi" 0K" dqj " vtcemi" 4" F QH" cpf "
 i kxgu" ulo r ng" hqtegu" kp" 4" F QH0 Vj g" Rj cpvqo " ðOmniöku" c" 5" F QH" hqteg" hggf dcmi"
 f gxleg0K" vtcemi" kp" 5" F QH" *tki j v/ rghv' kp/ qw. " cpf " wr / f qy p+ " cpf " i kxgu" hqtegu" kp" vj qug"
 uco g" F gi tggg" qh" Hggf qo 0' 5" F QH" f gxlegu" *cpf " j ki j gt" F QH" f gxlegu+ " ctg"
 uki p kHecpv" o qtg" eqo r ngz" vj cp" 4" F QH" f gxlegu0* Hki vtg" 4B+ "

"
 "

O cp{ "eqo o gtekn'eqo r cplgu'f gxgnr "5F "j cr vle'gej pqmri { "cpf 'r tqf weu'v'j cv'gpcdrig"
r gqr ng'v'g'zr gtlgpeg'c'tgcn'vle'ugpug'qh'vqvej O'Wukpi "vj gug'5F "j cr vle'f gxlegu'cpf "5F "
j cr vle"uqhy ctg."wugtu"ecp"hggn'5F "qdlgeu."hggn'vj gkt"uj cr gu"cpf "vgzwtgu."hggn'vj g"
f { pco le'r' tqr gt'v'gu'qh'qdlgeu."cpf 'hggn'o cp{ "qvj gt'gh'geu0"

Cnj qwi j "j cr vle'f gxlegu"j cxg"dggp"cxcl'cdrg"ht"eqo o gtekn'cr r'ncv'kpu"ht"o cp{ "
{ gctu."vj gug'f gxlegu"j cxg"j kvqt'kcm{ "equ'v'g'pu'qh'vj qwucpf u'v'j'j wpf tgf u'qh'vj qwucpf u"
qh'f qmctu0"

2.2 HAPTIC DEVICES AND HAPTIC INTERFACES

2.2.1 Physiology of Human Haptic Interface

Vj g"j cr vle" k'p'v'g'hegu"j cxg" cp" ko r qt'v'p'v' tqrg" kp"j wo cp" k'p'v'g'cevkqp" y kj " xlt'w'cn'
gpxktqpo gpw0'8: _"Vj g'x'k'w'cn'c'p'f'c'w'f'k'q't{ "u{ u'v'go u'c't'g'r'c'cm'q'h'ug'p'ul'pi "c'p'f'c'ev'k'p'i "q'p"
vj g" g'p'x'k't'q'p'o g'p'w'0' Vj g"j cr vle" u{ u'v'go u'c't'g'r'c'cr'cdrg" qh' d'q'v'j "ug'p'ul'pi "c'p'f'c'ev'k'p'i "q'p"
g'p'x'k't'q'p'o g'p'w'0"

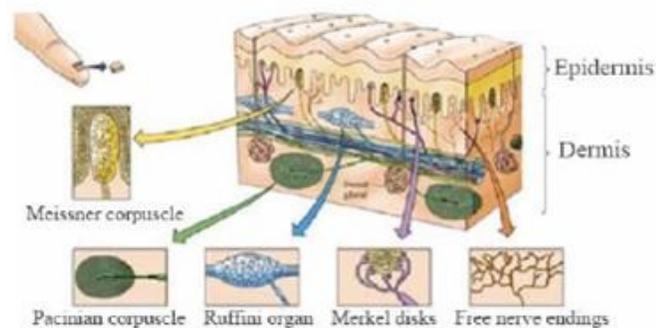
J wo cp'u'c't'g'c'drg'v'q'ug'p'ug'v'j g'v'q'vej "y kj "vj g't'gegr v'qtu'go dg'f'f'g'f' "kp'v'j gkt'unk'p'u."y j lej "
c't'g'r'c't'v'q'h'v'j g"ew'c'p'g'q'w'u"u{ u'v'go ."c'p'f'c't'gegr v'qtu."y j lej "c't'g'r'c't'v'q'h'v'j g"n'k'p'g'uj g'v'le"
u{ u'v'go ."h'q'ec'v'g'f' "kp'v'j g'o w'u'eng'u."v'g'p'f'q'p'u'c'p'f' "l'q'k'p'u0"

Vj g'f'f'k'ht'g'peg"dg'w' g'gp"vj gug"ku"dg'uv'k'm'w'ut'c'v'g'f' "d{ "cp"gzco r ng'0'U'w'r q'ug"vj g"j c'p'f "
j q'r'f'k'p'i "c'r'g'p'eqo gu'w'r "v'q'c'p'q'dl'ge'v'u'w'r g'p'f'g'f' "kp" ur'ceg0'Vj g'k'p'k'c'n'ug'p'ug'qh'eq'p'v'ce'v'
ku'r' t'q'x'k'f'g'f' "d{ "vj g'v'q'vej "t'gegr v'qtu'kp'v'j g'unk'p."y j lej "c'nu'q" r' t'q'x'k'f'g'k'p'h'q'to c'v'k'q'p'q'p'v'j g"
eq'p'v'ce'v'u'w'h'c'eg'i g'q'o g'v'x' { ."vj g'u'w'h'c'eg'v'g'z'w't'g'q'h'v'j g'q'dl'ge'v'0"

Y j gp" vj g" j c'p'f' "c'r'r'k'gu" o q't'g' h'q'teg." n'k'p'g'uj g'v'le" k'p'h'q'to c'v'k'q'p" eqo gu" k'p'v'q" r'nc{ "
r' t'q'x'k'f'k'p'i "f'g'v'c'k'u'c'd'q'w'v'j g'r'q'uk'k'q'p'c'p'f' "o q'v'k'q'p'q'h'v'j g"j c'p'f' "c'p'f' "c'to ."c'p'f' "vj g'h'q'tegu"
c'ev'k'p'i "q'p" vj gug."v'q"i k'x'g"c"ug'p'ug'q'h'v'q'v'cn'eq'p'v'ce'v' h'q'tegu." u'w'h'c'eg"eqo r'nc'peg."c'p'f' "
y g'k'i j v'0'Vj gug'v'ce'v'k'g'c'p'f' "n'k'p'g'uj g'v'le"ug'p'ul'pi "q'ee'w't'uko w'nc'p'g'q'w'u'0"Y j k'rg'v'ce'v'k'g'ku"
t'g'ur'q'p'uk'drg" h'q't" vj g" x'c't'k'v'k'q'p" q'h" vj g" unk'p" u'v'ko w'k' *g'0' x'k'd't'c'v'k'q'p." v'g'z'w't'g+." vj g"

nkpguy gve"ku"tgrvxf "v" j g"co qwpv"qh"hteg"gzgtvf"qp" j g"o wuerg0 Dqj "vcekrig"
 ugpukpi "cpf"nkpguy gve"ugpukpi "qeewt"eqpewtgpw(0j g"lphqto cvkqp"ej cppgn"lp"j g"
 j wo cp"j cpf "eqpukv"qh"j g"hqmy lpi "qh" ugpugt { "tgegr vtu="o gej cpqtgegr vqt. "j gto q"
 tgegr vqt. "pkekqegr vtu"cpf "r tqr tkqegr vqt0"

Vj g"o gej cpqtgegr vtu"ctg"mpqy p"cu"vwej "tgegr vtu. "tgecv"v"o gej cplecn"lpvgtcvkqp"
 dgw ggp"qdlgeu"cpf "j wo cp"unkp"cpf "eqpxg { "lphqto cvkqp"cdqw"ur cvkn"vgo r qtrncpf "
 vj g"utgpi vj "qh" vj g"hteg"v" j g"cr r tqr tkvg"qti cpu0 Vj g"uv"nwu"qh"j cr v"e" f gxleg"ku"
 o cplr wvxf "y kj "vj g"lpi gtvr u0 Vj g"lpi gtvr u"j cxg"ur gekn'o gej cpqtgegr vtu. "uwej "
 cu="öMeissner corpusleö."öPacinian corpuscleö."öRuffini organö."ömerkel disksö."cpf "
 öfree nerve endingsö" *Hki wtg"404+"

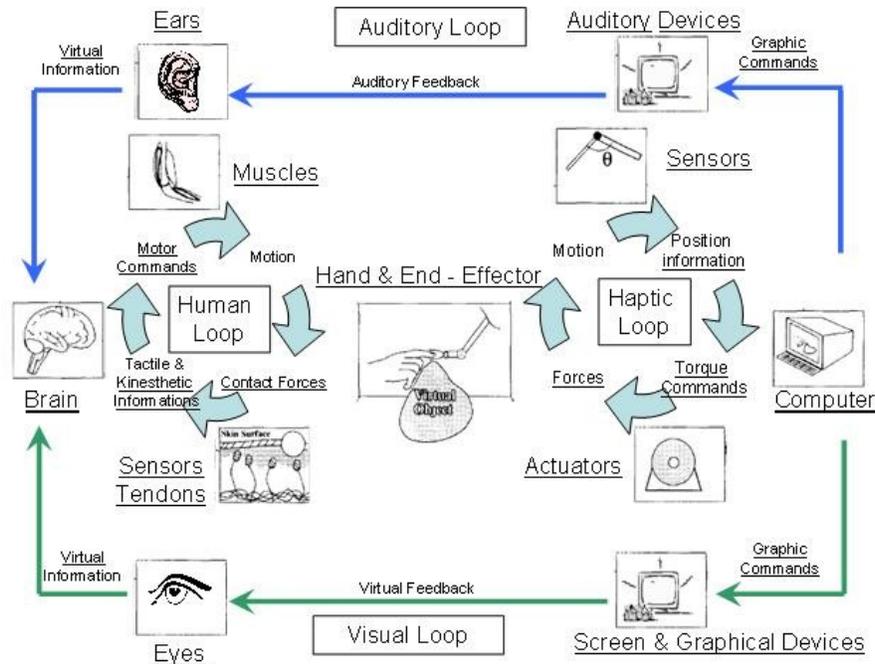


Hki wtg"404" J wo cp"Unkp"y kj "Vcekrig"tgegr vtu"

Vj g"vj tguj qrf "dcpf y kf vj u"qh"lphqto cvkqp"ej cppgn"j cxg"v" dg"mpqy p"v" r tqxkf g"
 o gcpkpi hwi"vcekrig"hgfdcen"v"vj g"vugt. "v"cxqkf "vugruu"hteg/hggfdcen"tgpfgt"vj cv"
 vj g"j wo cp"ecppqv"ugpug. "cpf "v"mpqy "j qy "qhv"vj gug"hteg/hggfdcen"j cxg"v" dg"
 i gpgtcvxf "lp" qtf gt" v" tgf weg" vj g" eqo r wcvkqp" vko g0 Kp" qj gt" y qtf u." c" i qqf "
 wpf gtucpf lpi "qh" vj gug" o gej cpqtgegr vtu" ku" guugpvkn' v" tgf weg" vj g" cni qtkj o "
 eqo r rgzkv { "cpf "v"o clpvclp"vj g"j cr v"e"vr f cvg"tcvg"qh"3"MI | 0"

2.2.2 Schematic of Human Haptic Interface

"
 Vj g"uwdu{uwo u" cpf "kphqto cvkqp" hny " wpf gtn{ kpi "kpvgtcevqpu" dgy ggp" wugtu" cpf "
 hqteg"o"tghngevki "j cr vle"kpvgthcegu"ctg"uwo o ctkt gf "d{ "j98_"uj qy p"kp"Hi wtg"40Vj g"
 wf cvg"tcvg"qh'ugpug"cpf "f kur x{ "qh"j wo cp"o"j cr vle"kpvgtcevqpu"o wuv'dg"3"MI | "cpf "52"
 J | "hqt"tgcnk{ "qh'xkt wcn'gpvktqpo gpwU'
 "
 "



Hi wtg"40" Uej go cvle"qh"j wo cp"o"j cr vle"kpvgthceg"

"
 "

40408"Rtko ct{ "j wo cp"o"j cr vle"kpvgthceg"Nqqr u"

"
 Cnj qwi j ."qwej "ku"uwcm{ "tghgtt gf "v"cu"c"ugpug."qwej "ku"o qtg"ceewtcvgn{ "c"i tqwr "qh"
 ugpu"r gtegxgf "v"j qwi j "v"j g"unp0"Vj gtg"ctg"uki pkkcpv"fhgtgpegu" dgy ggp"j wo cp"
 ugpu"qh"qwej "cpf "j wo cp"xlwcn"qt"cwf kqt{ "ugpu0"Vqwej "ku"wpks wg"cu"c"ugpu"cpf "
 v"r gtegxg"cp" qdlgev" v"j tqwi j "qwej ."eqpcev" ku"tgs wkt gf " y kj "v"j g" qdlgev" qt" uqo g"
 kpvgto gf lct{ "ugpu0"
 "
 "

"

J wo cp"Ugpuqtlo qvqt"Nqqr<"Y j gp" c"j wo cp"vqvej gu" c" xkt wcn' qdlgev" vj g" hqtegu" ctg"
ecwuf "d{ "ugpuqt{ "ukw wk0'Y j gp" c"j wo cp"vqvej gu" c" xkt wcn' qdlgev" vj g" hqtegu" ctg"
ko r qugf "qp" vj g" j wo cpw' unkp0' Vj g" cuuqekcvgf "ugpuqt{ "kphqto cvkqp" ku' eqpxgf gf "vq" vj g"
dtckp" cpf "ngcf u" vq" r gtegr vkp0' Vj g" o qvqt" eqo o cpf u" kuwgf "d{ "vj g" dtckp" cevkxcvg" vj g"
o wuergu" cpf "tguwn' kp" j cpf "cpf" cto "o qvkkp0"

"

J cr vke"Ugpuqtlo qvqt"Nqqr<"Y j gp" c"j wo cp"o cplr wrcvgu" vj g" gpf "o" ghgevqt" qh" vj g"
j cr vke" f gxleg. "vj g" r qukkqp" cpf "qtlgpcvkqp" ugpuqtu" qp" vj g" j cr vke" f gxleg" eqpxgf { "ku" vk r "
r qukkqp" cpf "qtlgpcvkqp" vq" vj g" eqo r wgt0' Vj g" r tqi tco "kp" vj g" eqo r wgt" ecrewrcvgu" vj g"
vqts wg" eqo o cpf u" f wg" vq" kpvgtcevkqpu" qp" xkt wcn' qdlgeu" cpf "ugpf u" vj g" ecrewrcvgf "
vqts wg" eqo o cpf u" vq" vj g" cewcvqtu" qp" vj g" j cr vke" f gxleg" kp" tgcni' vko g0' Vj gp"
cr r tqr tkcvgf "tgcevkqp" hqtegu" cpf "vqts wgu" ctg" cr r rkgf "qp" vj g" wugt" kp" qtf gt" vq" uko wrcvg"
vcewcn' ugpuq" qh' xkt wcn' qdlgeu" d{ "vj g" f gxleg" o qvqt0"

"

40404' Cwzkkct { "J wo cp" o" J cr vke" kpvgtcveg" Nqqr "

"

Vj gug" mqr u" ctg" pqv' ucwgf " kp"]98_ " cpf " qvj gt" uwf kgu0' Cmj qwi j " vj gug" mqr u" ctg"
ugeqpf ct { "kp" j cr vke" kpvgtcveg. " vj gtg" j cxg" i tgcv' tqng" kp" j cpf "o" g{ g" eqqtf kpcvkqp0' D{ "
vj g" j gr "qh' xkuwcn' cpf " cwf kqt { "mqr " kp" vj g" j cr vke" u{ ugo . "wugt" ecp" ugpuq" vj g" i tcr j leu"
cpf " cr r rkecvkqp" dgwgt0' Vj gtg" ctg" ur gekni' gs wkr o gpw" hqt" dqj " xkuwcn' cpf " cwf kqt { "
mqr 0' Vj g' y kf g' uetggp" NEF " o qpkqtu' y kj " hcu' tgh' guj " tvkq. "5" f ko gpukqpcni' r tqlgcvkqp"
f gxlegu. " cpf " ur gekni' "5" f ko gpukqpcni' i rcuugu" wukpi " uvgtgq" i tcr j leu" cmqy u" wugt" vq"
ugpuq" qdlgev' xkuwcn' 0' Vj g" uvgtgq" uqwpf " f gxlegu" cpf " j gcf r j qpgu" cmqy " wugt" vq" j gct"
vj g" cr r rkecvkqpu" cpf " tguwnu' vj cvj g" r gthqto u0'

"

J wo cp"Xkuwcn'Ugpuqtlo qvqt"Nqqr<"Y j gp" c"j wo cp"o cplr wrcvgu"vqvej gu"qt"o cngu"
cp{ "qr gtcvkqp" qp" xkt wcn' qdlgeu. "vj g" r qukkqp" qh' vj g" xkt wcn' qdlgeu" qp" vj g" i tcr j lecn'
f gxleg" ku" ko r qugf " qp" vj g" j wo cpw' g{ gu0' Vj g" cuuqekcvgf " ugpuqt{ " kphqto cvkqp" ku"
eqpxgf gf "vq" vj g" dtckp" cpf "ngcf u" vq" r gtegr vkp" y kj " vj g" qvj gt" j wo cp" ugpuqtlo qvqt"
mqr u0'

"

"

J wo cp'Cwf kqt { "Ugputko qvt "Nqqr <Y j gp'c"j wo cp'o cngu'cp { "qr gtcvkqp"qp'xkt wcn'
qdlgeu'rnng'f tkkpi "qr gtcvkqp."vj g'uqwpf "qh'vj g"qr gtcvkqp"qh'xkt wcn'qdlgeu'qp"vj g'
uqwpf "f gxleg'ku"ko r qugf "qp"vj g"j wo cp'g'ctu'Vj g'cuuqekv'f "ugput { "kphqto cvkqp"ku"
eqpxg { gf "v"vj g"dtckp"cpf "ngcf u"v"r gtegr vkqp"y kj "vj g"qvj gt"j wo cp"ugputko qvt"
mqqr u0"

"

2.2.3 Types of Haptic Devices

"

Vj gtg"ctg"ugxgtcn'f khtgpv'v' r gu"qh"j cr v' f gxlegu'J cr v' f gxlegu'f khtg"kp"vj gkt"
pwo dgt"qh"FHu" *F gi tgg"Qh" Hggf qo +."vj gkt"j cr v' hggf dcn'dgkpi "rtqxf gf" d { "
f gxlegu."vj gkt"eqputwvkqp."cpf "vj gkt"cdkxv' "v'i gpgtcv'f khtgpv'v' r gu"qh" qwr wu'0k"
i gpgtcn'y g'ecp'f kxkf g'j cr v' f gxlegu'kp'v'4 'o clp'i tqwr u'd { "vj gkt"eqputqn'v' r gu'Vj gp."
y g'ecp'wd'i tqwr "vj g'j cr v' f gxleg'd { "vj gkt"eqputwvkqp'v' r gu'0

"

40408'Eqputqn'qh'J cr v' f gxlegu'

"

Vj gtg"ctg" y q" v' r gu"qh" j cr v' f gxlegu" d { "vj gkt" eqputqn' f kxkf rkp'0 Vj g" v'gto u"
ko r gf cpeg'cpf "cf o kvcepeg'eqo g'htqo "cp'cpcmi { "y kj "grgestqple"ektewku'0

"

kp'o gej cplecn'u'ugxo u."cf o kvcepeg'ku" c'f { pco le"o cr r kpi "htqo "hqteg"v"o qvkqp'0kp"
qvj gt"y qtf u."cp"gs wcvkqp" f guetkdkpi "cf o kvcepeg"y qwr "j cxg" kpr wu"qh" hqteg"cpf "
y qwr "j cxg"qwr wu"uwej "cu'r qukxqp"qt "xgmekv' (0Uq."cp"cf o kvcepeg'f gxleg"y qwr "
ugpug'vj g'kpr w'hqteg"cpf "scf o ksc"egtckp'co qwpv'qh'o qvkqp'0

"

Uko kxt"v"vj g"grgestkcn'o gcpkpi u"qh'cf o kvcepeg"cpf "ko r gf cpeg."ko r gf cpeg"kp"vj g"
o gej cplecn'ugpug"ecp"dg"vj qwi j v'qh'cu"vj g"skpxgtug\$ "qh'cf o kvcepeg'0Vj cv'ku."k'ku" c"
f { pco le"o cr r kpi "htqo "o qvkqp"v' hqteg'0Cp'ko r gf cpeg'f gxleg"y qwr "ugpug'vj g'kpr w"
o qvkqp"cpf "sko r gf g\$'vj g'o qvkqp"y kj "uqo g'hqteg'0

"

Cp'gzco r ng'qh'vj gug'eqpegr u'ku'c'xkt wcn'ur tkpi 0Vj g'gs wcvkqp'f guetkdkpi "c'ur tkpi "ku"
J qqng'u'Ncy ."

"

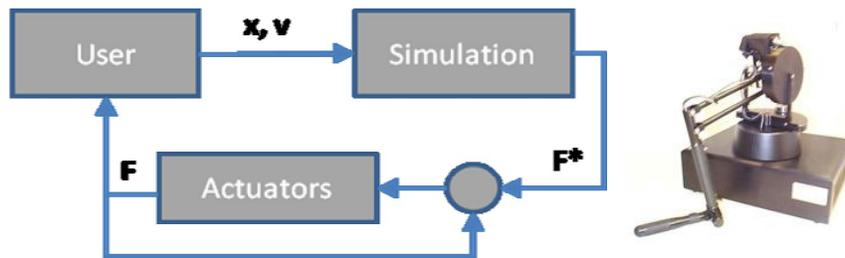
"

$$F = k\Delta x \quad (2.1)$$

"
 K'i'j g"lpr w'v'j g'xkt wcn'ur tkpi "ku'j g'ur tkpi "f kur mrego gpv."z."cpf "j g"qwr w'ku'j g"
 hqteg"j cv'j g'xkt wcn'ur tkpi "cr r nkgu."H"j gp"j g'xkt wcn'ur tkpi "y qwf "dg"emcukhgf "cu"
 ko r gf cpeg0K'i'j g"lpr w'v'j g'xkt wcn'ur tkpi "ku'j g'hqteg"cr r nkgf "v'j g'ur tkpi ."H"cpf "
 j g"qwr w'ku'j g'ur tkpi "f kur mrego gpv."z."j gp"j g'xkt wcn'ur tkpi "y qwf "dg"emcukhgf "cu"
 cf o kwcepg0

"
 4040303'K'o r gf cpeg'F gxlegu<

"
 Vj g"ko r gf cpeg'f gxlegu"ugpug"r qukkqp"cpf "xgrnek{ "qh"j g'f gxleg0Vj g{ "ctg"wgf "kp"
 j g"uko wcvkqp"v"o qxg"cp"qdlgev'r qkpv'hp0Vj ku"qdlgev'kpgtcew'y kj "j g"uegpctkq0
 Hqtegu"ctg"eqo r wgf "cpf "tgwtpgf 0'O qxkpi "j g"cewcvqtu"qh"j g"o qvqt "ku"v"r tqf weg"
 j qug'hqtegu0Vj g"j cr v'e'tgpf gt kpi "kpxqixgu"eqmkukqp"f gvgev'kqp"cpf "c"eqpcev'tgur qpug"
 o qf gn' v" eqo r wg" j g" hqtegu0 F wg" v" eqmkukqp" f gvgev'kqp" cpf " eqpcev' tgur qpug"
 ecr cdkkkgu."ko r gf cpeg"dcugf "j cr v'e" f gxlegu"ctg" j g"o quv'r qr wct "v{r g"qh"j cr v'e"
 f gxlegu0"



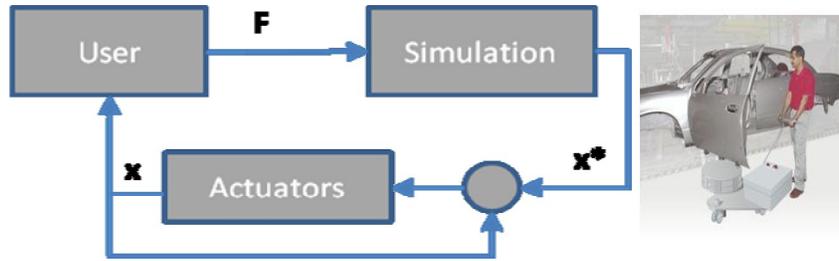
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"
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 hqtegu" j gp" hpf " r qukkqp" eqputckpw" cpf " o qxg" j g" f gxleg" ceeqtf kpi " v" j qug"
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dwmgk" cpf " o qtg" gZR gpukxg" cpf " kv" ku" wugf " kp" eqmkukqp" f gvgevqp" cpf " r qukkqp"
eqpwtckpw'o qf gnu0

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"
"

404504'Utwewtgu'qh'J cr v'e'F gxlegu'

"

K'ku'r qukkdrg'v'q'i tqwr 'j cr v'e'f gxlegu'kp'v'q'hqwt'o clp'i tqwr u'f wg'v'q'utwewtgu'qh'j cr v'e'
f gxlegu0

4045048'F gumio'Dcugf 'J cr v'e'F gxlegu<

"

Vj g'RJ CP VqO "j cr v'e'f gxlegu."uj qy p"kp'Hki wtg"40."ctg'vj g'o quv'y kf gn' (wugf 'hqteg"
hggf dcm' f gxleg0 " K' ku' f gxgnr gf " cv" O K'" cpf " pqy " o ctngvf " d{ " UgpuCdrq"
Vgej pqmji kgu"]97_0' K'r tqxkf gu" hqteg" hggf dcm' v'q" c" uv' n'wu' urk r gf " qxgt" vj g" wugt'au"
j cpf 0'Vj g'RJ CP VqO 'f gxleg'cmqy u'wugtu'v'q'o qxg'ht ggn' 'kp'8'f gi tgg'q'h'ht ggf qo "z."
{.} . 'tqm'r kej 'cpf "{cy +0"

"

Vj g'r qukkqp'ugpuqtu"*qr v'ecn'gpeqf gtu'+ctg'wugf "v'q'o gcuwtg'vj g'r qukkqp'qh'vj g'wugt'au"
o qxgo gpv'u."y kj "qpg" gpeqf gt" d'gkpi "o qwpv'gf " qp" gcej "qh'5" FE" dtwuj gf "o qvqtu0"
Vj gug'5'FE" dtwuj gf "o qvqtu'i gp'gtcv'g" hqtegu'kp'vj g'z."{ 'cpf 'l "eqqtf k'pcv'gu0'J qy gxgt."
vj g'ucpf ctf " RJ CP VqO "o qf gnu'f q" pqv' r tqxkf g' hqteg" hggf dcm' kp' vj g' tqv'kqpcn'
f lo gpukqpu0'Vj g'RJ CP VqO "8F QH'f qgu" r tqxkf g' tqv'kqpcn' hqteg" hggf dcm'0'Vj gug'
j cr v'e' f gxlegu" i gp'gtcv'g" vj g' v'qts wgu" ctg" r cuugf " vj tqwi j " c" r tg/v'gpukqpgf " ecdrg"
v'cpuo kuukqp'v'q'vj g'h'kp'mei g0"

"

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kp'qwt'uwf lgu.'y g'wug'dqvj 'vj g'RJ CP VqO 'Qo pk'Hki wtg'480+'cpf 'Rtgo kwo '*Hki wtg'
 480l+'j cr v'e'f gxlegu'Vj g'f gxleg'r tqxkf gu'c'o czko wo 'qh'cr r tqzko cvgn' '32'P gy vqpu'
 qh'hqteg'hqt'uj qt v'r gtlqf u'cpf " cr r tqzko cvgn' '306'P gy vqpu'qh'eqpv'kwgu'hqteg'0Vj ku'ku'
 uwhlekgpv'hqt'o quv'kvgtcevkqpu'vj qwi j v'vj g'lv'nu'ORgcug'ugg'vj g'Cr r gpf kz " hqt'f gvckn'
 qh'j cr v'e'f gxlegu'vj cv'tg'wugf 'kp'qwt'uwf {0

"
 "



C+Vj g'RJ CP VqO 'Qo pk'J cr v'e'f gxleg'y kj " 5F QH'Hqteg'Hggf dcenti



D+Vj g'RJ CP VqO 'Rtgo kwo 'J cr v'e'f gxleg' y kj '8F QH'Hqteg'Hggf dcenti

Hki wtg'48" Vj g'RJ CP VqO 'J cr v'e'f gxleg'"

"
 "

Vj gtg'ctg'qvj gt'eqo r cpkgu'vj cv'tg'f gxgnr gf "RJ CP VqO 'v'r g'j cr v'e'f gxlegu'uwej "
 cu="Hqteg'F ko gpukpau'Qo gi c'j cr v'e'f gxleg"cpf "F gnc"j cr v'e'f gxleg"cpf "O RDau'
 Ewdle'J cr v'e'f gxleg."Uekuqtu'cpf "Hggf qo "ctg'uqo g'qh'vj g'eqo o gtekm{/cxckrdrg"
 f gumio'dcugf "j cr v'e'f gxlegu'0"

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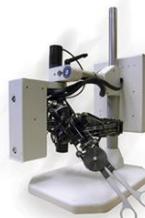
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O RDau'Ewdle'j cr v'e'f gxleg'



O RDau'Uekuqtu'J cr v'e"



O RDau'Uekuqtu'Hggf qo 'f gxleg' f gxleg"

Hki wtg'40" Qvj gt'RJ CP VqO 'V'r g'j cr v'e'f gxlegu'"

"

Vj gtg"ctg"qvj gt "f guni'ó"dcugf "j cr vë "f gxlegu"uwej "cu="Vj g"uvgtkpi "y j ggnu"ht "xkf gq" tceg"i co gu"gpdrp"hteg"ó"hgfdcent'cpf "xkdtcvkqp"y j gp"vj g"tceg"ect"ku"vqvej kpi . " dwo r kpi "qvj gt'ectu"qt"y cmu'f vt kpi "vj g"i co g0*Hki wtg"40 Qe+"

"

Vj g"uwti kecn'uekuqt "j cxg"vy q" f gi tggu"qh"htggf qo . "qpg"ht "eww kpi "tqvcvkpcn"cpf " qpg"ht "tcpuvcvkpcn"j82_0Vj ku'f guni'ó"dcugf "j cr vë "f gxleg"ku'f gxgnr gf "cpf "wugf "ht " uwti kecn'vtckp kpi u'kp"qtf gt "vq"cmqy "vj g"vugtu"vq"i ckp"xkt wcn'gzr gtlkpeg0*Hki wtg"40 Qd+" Vj g"j cr vë "óKF tkxg"Eqpvtqmgto" f gxgnr gf " d{ "DO Y "y kj "K o gtukqp"Eqqr gtcvkqp" o cnkpi "r quukdrp"vq"eqpvtqn'hcwttgu"kp"DO Y "9"ugtkgu'd{ "pcxki cvkpi "f khtgpv'o gpwu" y kj "vj g" f khtgpv'hteg"r cwgtpu0*Hki wtg"40 Qe+"

"

Vj ku" u{uvgo " cmqy u" f tkxgtu" vq" ceeguu" pwo gtqwu" qr gtcvkqpu" uvej " cu" erko cvg." gpvgtckpo gpv."cpf "pcxki cvkqp"y kj "c"ukpi rg" eqpvtqn' Vj g"KF tkxg"hcwttgu" c"ukpi rg" eqpvtqn'f kcn'o qwpvqf "qp"vj g"egpvt"eqpuqrq0'Vj g"eqpvtqmg"cmqy u" c" f tkxgt"vq"j cxg" kpuvcpv"cpf "vqcn'eqpvtqn'qh' gxt { "eqo hqtv" grgo gpv'kp"vj g"ect. "htqo "vj g"qp/dqctf " pcxki cvkqp"u{uvgo "vq"vj g"ck"eqpf kkpqgt"vq"vj g'o qdkrg'vgrgr j qpg."vj tqwi j "vj gk"ugpug" qh'vqvej 0' C" f tkxgt"ecp"urkf g"vj g" f kcn'vq"ej qqug"dgwy ggp"o wnk rg" eqpvtqn'o gpwu" f kur r: {gf "qp"cp"kp/fcuj "NEF" uetggp."tqvcg" k'vq"o qxg"vj tqwi j "rkua."cpf "r wuj "k' czkcm{ "vq"ugrgev" c"rkuv'kgo 0'O kpo k kpi "f cuj dqctf "enwgt"cpf "o czko k kpi "wucdkkv{ " qh'cwqo qdkrg"eqpvtqn'hwpevkqpu."vj g"óiDriveö"ku'kf gcn'ht"j gr kpi "f tkxgtu"nggr "vj gk" g{gu"qp"vj g'tqcf 0]34_"

"

"



Uvggtkpi "Y j ggrl"



Uwti kecn'Uekuqtu'



J cr vë 'KF tkxg"

Hki wtg"40 " Qvj gt'F guni'ó'Dcugf "J cr vë 'F gxlegu'

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405040'C wej gf "J cr v'e'F gxlegu<

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C wej gf "j cr v'e'f gxlegu"j cxg"vj g"cf xcpwi g"vq"dg"eqo r cev0Vj gug" j cr v'e'f gxlegu'ctg"
r tghgtgf "hqt" f khtgtpv'htpf u'qh'cr r r'ecv'kpu'hqt" f kucdrf "r gqr ng0Uqo g"qh'vj gug"j cr v'e"
f gxlegu'ctg"cnuq"r qtvdng" f gxleg"uq"vj cv'wugu"eqwf "ectt{ "vj g"j cr v'e'f gxleg"y kj "vj gkt"
ugr'gu0Vj g"J cr v'eI gct"qh"J ktqug"ku'uko kxt"vq"vj g"vgpukqp"o"dcugf "u{ uvgu "j cxkpi "cnuq"
c" uv{ nnu" yj cv' ku" eqppgevgf " vq" f gxleg" j qrf " qp" vj g" dcent' y kj " ecdngu0' Vj g" XVku"
E{ dgtVqwej "tgpfgtu'xkdtcvkqp"vq"hw' hpi gtvr u'lp"qtf gt"vq"r tqxkf g'ggf dcent0'

"

"



c+ J cr v'e'I gct"



d+ E{ dgtVqwej "

Hki wtg"40 " C wej gf "J cr v'e'F gxlegu'

"

"

Vj g" E{ dgtI tcur." E{ dgtHqteg" cpf " E{ dgtVqwej " *Hki wtg" 402+" f gxgrqr gf " d{ "
K o gtukqp"j cxg"3; "f gi tgg"qh"htggf qo 0'Vj gug"j cr v'e'f gxlegu"cpf "u{ uvgu u'ctg"xgt{ "
gxr gpukxg"fvq"vj ku"j ki j "f gi tgg"qh"htggf qo 0"

"

Vj g"pgy "y ktgruu"E{ dgtI nrxg"KKu{ uvgu "ku" c" hnm{ "kputwo gpvgf "i nrxg"vj cv'r tqxkf gu"
wr "vq"44"j ki j /ceewtce{ "lqkv/cpi ng"o gcuwtgo gpv0K'wugu'r tqr tkgvct{ "tgukv'xg"dgpf/
ugpukpi "vgej pqmji { "vq"ceewtcvgn{ "tcpuhqto "j cpf "cpf "hpi gt"o qv'kpu"kpq"tgciz'v'o g"
f ki kcn'lqkv/cpi ng"fcv0'

"

"



"

c+ E{dgtI mxxg"



"

d+ E{dgtI tcur"



"

e+ E{dgtI tcur "U{uigo "

Hki wtg"402"J cr vle"l mxxg"Vgej pqmji {"

"

"

Vj g"Gzqungngvqp"Hqteg"Cto O cuvgt."GCO "KKk" f gxgnqr gf "d{ "GZQU"cpf "vj ku"j cr vle" f gxleg" j cu" 7" f gi tgg" qh" htggf qo " cpf " cf f kklqpcn" r cuukxg" htggf qo u" f guki pgf " hqt" eqo hqt"cpf "vj g"cdkxv{ "v"cf lwuv" f hhtgtpv"cto "uk gu0"Hki wtg"403+"

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Hki wtg"403"Vj g"Gzqungngvqp"Hqteg"Cto O cuvgt."GCO "KKJ cr vle" f gxleg"

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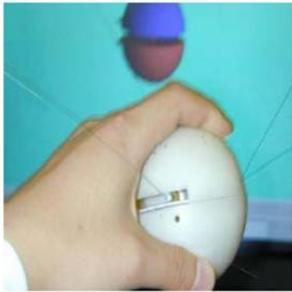
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Hki wtg"404"Vgukqp"Dcugf "J cr vĕ"F gxlegu"

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404040'Eqo dĕpgf "J cr vĕ"F gxlegu<

"

Eqo dĕpgf "j cr vĕ" f gxlegu" ctg" dwnĭ "cpf "xgt { "gzr gpukxg0' Vj g { "ctg" eqo dĕpĕvkp" qh" f kĭhtg pĕv' j cr vĕ" f gxlegu" y kj "xkwnĭ" uvgt gq" i rĕuugf "kp" qtf gt" vĕ" uko wĕvĕ" vj g" xkt wĕrĭ' gp xkt qpo gpv' y kj 'hwnĭ' "dqf { 'hggf dĕcĕn0'

"

"RGTEtQ" rĕdqĕvĕt { " j cu" cp" gzqungrgvq" f gxleg" hqt" uko wĕvĕpi " vj g" f tkxĕpi " hqt" eqĕm k' f guki p" qr vĕo kĭ cĕvkp0' *Hki wtg"405+" "Vj g" wugt" ecp" hggĭ' vj g" uko wĕvĕkp" vj g" f tkxĕpi "y kj "j kĭ j "f gi tgg" qh' h' tggf qo "y kj "vj g" j' gĕr "qh' vj g" ur gĕkĕrĭ' rĕuugu0'

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Hki wtg"405"RGTEtQa'F tkxĕpi "Uko wĕvĕkp" Eqo dĕpgf "J cr vĕ" F gxleg"

"

Vj g' ĩĕqo qvĕxg' eqo dĕpgf "j cr vĕ" f gxlegu" ctg" vj g' ĕpĕvĕtĕĕgu' y kj 'hwnĭ' "dqf { 'hggf dĕcĕn0' Vj g' u' f gxlegu" f q" pĕv' tĕgĕtĕv' j wo cp" o qdĕkĕv { " uĕej " cu" y cĕmĕpi " qt" tĕwĕpĕpi 0' Vj g" Y cĕmj tqwi j "j cr vĕ" f gxleg" r tqxĕf gu" vj g' wugtu" c" hggĕrĕpi "qh" r tĕgĕpĕg" ĕp" vj g" xkt wĕrĭ'

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gp xktqpo gpv'0' k'p" vj ku" k'p vgt hceg. " vj g" qdlgevu" cni' vj g" qdlgevu" ctg" r ctv" qh' vj g" xkt wcn'
gp xktqpo gpv. hqt "gzco r ng. "wugt "ecp" r wuj . 'r wni' c'p' f' i' tcur gf 'vj g' cni' vj g' qdlgevu0''''

"



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Hki wtg'406" Vj g'Y cmj tqwi j 'J cr v' k'p vgt hceg'

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"

2.2.4 Types of Haptic Applications

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Vj gtg" ctg" pwo gtqwu" f gxgnr gf " j cr v' k'p " cr r n'ecv'k'pu" f wg" vq" xkt wcn' tgcni' { " pggf " k'p"
vqf c { au' v'ej pqmji { 0' k'p " o cp { " ctgcu. " xkt wcn' tgcni' { " ku" wugf " dw' y kj " vj g" cf f k'k'p'cni'
j cr v' k'p " f gx'legu. " vj g' xkt wcn' tgcni' { " dgeqo gu' o qtg' tgcni' k'p " c'p' f' r qr w'ct0''

"

J cr v' k'p " ku" cr r n'ecv'k'pu" hqt" o quv' qh' vj g" ctgcu" qh' eqo r w'k'p i " k'p'cni' k'p i " k'p' f' w'ct { "
cr r n'ecv'k'pu. " gpv'gt'v'k'po gpv' cr r n'ecv'k'pu. " o gf k'ek'p g" cr r n'ecv'k'pu. " gf w'ecv'k'p " c'p' f' "
v'ek'p'k'p i " cr r n'ecv'k'pu. " ctv' c'p' f' " etg'v'k'p " cr r n'ecv'k'pu. " o ctng'v'k'p i " cr r n'ecv'k'pu. " c'p' f' "
o k'k'ct { " cr r n'ecv'k'pu0''

"

404060 k'p' f' w'ct { " Cr r n'ecv'k'pu" "

"

Eqo r wgt " Ck' gf " F guki p " *ECF +]97_ " Eqo r wgt " Ck' gf " O cpw'c'ewt'k'p i " *ECO + " v'q'ni "
]9: _ " xkt wcn' r tqv'v' r k'p i . " xgj k'eng" qr g'c'v'k'pu" c'p' f' " eqp'v'q'ni' tq'qo u" wug" vj g" j cr v' k'p "
v'ej pqmji { " hqt " k'p' f' w'ct k'ni' r w'tr q'gu0' Hqt " gzco r ng. " cp " c'k' r n'epg " t'wddgt " r gf cni' j cu " dggp "
cuugo dn { " k'p " gp xktqpo gpv' d { " w'k'p i " j cr v' k'p " v'ej pqmji { 0']44_ " k'p " c " ECO " uko w'ecv'k'p " qh' "
o cej k'k'p i " r tqegu. " j cr v' k'p " v'ej pqmji { " wugf " hqt " uko w'ecv'k'p " qh' f' gh' to c'v'k'p. " eww'k'p i . "
w'p'k'p i . " f' t'k'k'p i " c'p' f' " o k'k'p i " r tqegu0']: 7_ "

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Hki wtg'4087'Ct'v'cpf 'Etgcvkqp'Cr r rdecvkqpu"

"

"

J cr v'k'dcugf 'xkt wcn'o wugwo 'cr r rdecvkqpu'r tqxkf g'v'g'zr mtg'vj g'xkt wcn'o wugwo 'cpf "

"

4040800 ctngv'pi 'Cr r rdecvkqpu"

"

Kpvtcevkxg'ecv'nci wgu'wulpi "j cr v'k'v'gej pqmji { "ctg" wugf "hqt" o ctngv'pi O'Xkt wcn'r tqf wewi' ctg'uko wrcvf "lp" xkt wcn'gp'xktqpo gpv'cpf "d { "vj g'j gr "qh'vj g" j cr v'k'f gxleg. "ewuqo gtu'ecp" v { "vj g'r tqf wewi']97_"

"

4040900 k'kct { 'Cr r rdecvkqpu"

"

J cr v'k'cr r rdecvkqpu'ecp'cnuq'dg'wugf "hqt" o k'kct { "vtcklpi "cpf 'uko wrcvkqpu. "g'f O'cv'vj g" Cto { au'P cvkqpcn' Cwqo qv'xg' Egpvt. "vj g' Uko VNE " *Vj g' Uko wrcvkqpu" vj tqwi j qw' vj g' N'kg" E { eng+ "]78_" wug' xkt wcn' tgc'kv { " hqt" v'g'ulpi " o k'kct { " xg' k'engu" lp" dcw'gh'grf " eqpf k'kqpu' Kp' cf f k'kqpu. " vj g' P cxcn' Cgtqur ceg" O gf k'ecn' Tgugctej " Ncdqtcvqt { " j cxg" f guki pgf "c" o'Vcevk'g' Ukwcvkqpu' Cy c tgp'guu' U { u'vgo o']79_" r tqxkf lpi 'r tgekug' qt'k'pvcvkqpu" k'phqto cvkqpu" lp" r'cpf. " ugc" cpf " vj g' cgtqur ceg" gp'xktqpo gp'u' vq" q'xg'eqo g' r tqd'rgo u" t'gr'v'gf "v'ur cv'cn'f kuqt'k'pvcvkqpu" qh'vj g'r k'qv'ecwugf "d { "gttqtu'y j k'ej "o ki j v'q'ee'w' h'qo "" o qo gpvct { " f k'utcevkqpu. " tgf w'egf " x'k'ld'k'kv { " qt" cp" k'petgcugf " y q'tm'q'cf O' H'g'pej " Cto { " j cu'wugf " vj g' Rj cp'vqo " r tgo kwo " f gxleg' hqt" r'cpf " o k'pg' engctcpeg' vtcklpi O' Vj g' u'v' nuu' y cu'wugf " vq' n'q'ecv'g' r q'v'p'v'cn'o k'p'gu'lp'v'q' vj g' xkt wcn'i tq'w'pf O'

"

"

"



Vcevkq'Ukwcvkq'Cy ctgpguu'U{ ugo "

Vj g'j cr vlc'Cr r rlecvkq' hqt' hqecvkpi 'yj g'
o kpgu0'

Hki wtg'4087" O ktkct { 'J cr vlc'Cr r rlecvkqpu"

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CHAPTER 3

HAPTIC RENDERING

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J cr v̄e"tgp̄f ḡtk̄pi "ku"r̄tq̄egu"y j̄ k̄ej "gp̄cd̄rgu"wūgt"v̄q"v̄q̄wēj . "hḡgr̄i"cp̄f "o c̄pk̄r w̄rc̄v̄g"xt̄w̄cn̄l̄
q̄dl̄geu"y k̄j̄ k̄p"̄c"xt̄w̄cn̄l̄y q̄tr̄f 0"J cr v̄e"tgp̄f ḡtk̄pi "ku"l̄p̄en̄x̄f̄ gu"̄"*graphical rendering*".
"*collusion detection*".cp̄f "̄"*haptic force feedback*"0V̄j̄ ḡug"o c̄k̄p"̄tgp̄f ḡtk̄pi "r̄t̄k̄p̄ek̄r̄ r̄gu"
ct̄g"cm̄l̄f̄ gr̄ gp̄f̄ gp̄v̄"v̄q"̄gcej "q̄v̄j̄ ḡt0K̄"ku"̄f̄k̄t̄geu"̄{ gh̄hḡev̄k̄pi "y j̄ k̄ej "i t̄cr̄ j̄ k̄ec̄n̄l̄tgp̄f ḡtk̄pi "
c̄n̄i q̄tk̄j̄ o "w̄uḡf "y j̄ gp̄f̄{ q̄w̄ct̄g"ej̄ ḡen̄k̄pi "h̄qt"̄c"eq̄m̄k̄uk̄q̄p"̄qt"̄uḡgn̄k̄pi "h̄qt"̄c"̄h̄q̄teg"̄hḡgf̄ d̄cen̄l̄
f̄ w̄g"̄v̄q"̄v̄j̄ ku"̄eq̄m̄k̄uk̄q̄p0K̄p̄"̄v̄j̄ ku"̄ej̄ cr̄ v̄gt̄. "i t̄cr̄ j̄ k̄ec̄n̄l̄tgp̄f ḡtk̄pi "cp̄f "̄eq̄m̄k̄uk̄q̄p"̄f̄ ḡv̄gēv̄k̄q̄p"̄y k̄n̄l̄
d̄g"̄f̄ k̄uēwūuḡf 0V̄j̄ g"̄j̄ cr̄ v̄e"̄h̄q̄teg"̄ hḡgf̄ d̄cen̄l̄ r̄t̄k̄p̄ek̄r̄ r̄g"̄y k̄n̄l̄ d̄g"̄f̄ k̄uēwūuḡf "̄k̄p"̄v̄j̄ g"̄ p̄gz̄v̄
ej̄ cr̄ v̄gt0

"

3.1 GRAPHICAL MODELING AND GRAPHICAL RENDERING

"

I t̄cr̄ j̄ k̄ec̄n̄l̄tgp̄f ḡtk̄pi "ku"̄cēv̄"q̄h"̄et̄gc̄v̄k̄pi "c"̄v̄j̄ t̄gg"/"̄f̄ k̄o gp̄uk̄q̄p̄cn̄l̄q̄dl̄gēv̄"̄ceēq̄tf̄ k̄pi "v̄q"̄c"
o q̄f̄ gr̄l̄y k̄j̄ k̄p"̄c"̄eq̄o r̄ w̄gt0V̄j̄ g"̄i t̄cr̄ j̄ k̄ec̄n̄l̄tgp̄f ḡtk̄pi "h̄k̄gr̄f "ku"̄q̄pg"̄q̄h"̄v̄j̄ g"̄o qūv̄l̄o r̄ q̄t̄w̄cp̄v̄"
ct̄gcu"̄k̄p"̄xt̄w̄cn̄l̄t̄gcr̄k̄v̄ "̄d̄gēcw̄ug"̄q̄h"̄ku"̄ēcr̄ c̄ek̄v̄{ "v̄q"̄r̄t̄q̄f̄ w̄eg"̄c"̄ō *realistic*̄"̄m̄q̄m̄k̄pi "y q̄tr̄f 0
K̄"̄ku"̄f̄k̄t̄geu"̄{ t̄gr̄c̄v̄ḡf "̄y k̄j̄ "̄eq̄m̄k̄uk̄q̄p"̄ f̄ ḡv̄gēv̄k̄q̄p"̄ d̄gēcw̄ug"̄ k̄v̄ f̄ gūet̄k̄d̄gu"̄ y j̄ k̄ej "̄o c̄k̄p"
i t̄cr̄ j̄ k̄ec̄n̄l̄t̄gr̄t̄guḡp̄v̄k̄q̄p"̄ku"̄w̄uḡf 0"

"

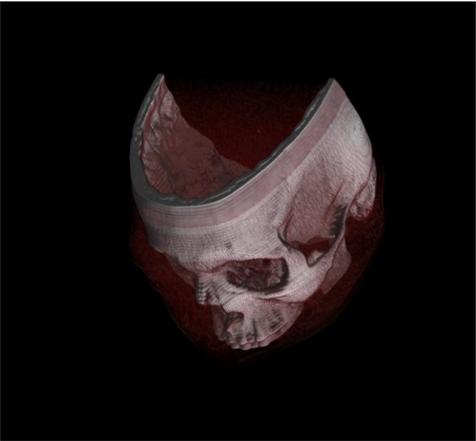
V̄j̄ ḡtg"̄ct̄g"̄y q"̄o c̄k̄p"̄i t̄cr̄ j̄ k̄ec̄n̄l̄t̄gr̄t̄guḡp̄v̄k̄q̄pu."̄ "*volumetric based*"̄"̄cp̄f "̄"*surface
based*"̄"̄i t̄cr̄ j̄ k̄ec̄n̄l̄t̄gr̄t̄guḡp̄v̄k̄q̄p0V̄q"̄uwo o c̄tk̄ g."̄j̄ cr̄ v̄e"̄tgp̄f ḡtk̄pi "y g"̄ct̄g"̄k̄p̄v̄gt̄guḡf̄"̄k̄p"
gh̄h̄k̄ep̄v̄."̄t̄q̄d̄wu"̄cp̄f "̄j̄ k̄i j̄/s̄w̄cn̄l̄{ "̄c̄n̄i q̄tk̄j̄ o u"̄v̄q"̄tgp̄f ḡt"̄v̄j̄ g"̄xt̄w̄cn̄l̄gp̄x̄k̄t̄q̄po gp̄vu"̄v̄j̄ c̄v̄
ct̄g"̄uwh̄h̄k̄ep̄v̄{ "̄h̄k̄ng"̄v̄j̄ g"̄t̄ḡcn̄l̄q̄pgu"̄cp̄f "̄w̄ug"̄k̄v̄h̄q̄t"̄eq̄m̄k̄uk̄q̄p"̄ej̄ ḡem̄l̄0

"

3.1.1 Volumetric Based Graphical Rendering

"
Xqno g"tgpfgtkpi "ku"vgej pks wgv"vugf "vq"fkur m{"c"4F "r tqlgvqpp"qh"5F "f kvetgvgn " uco r rpf "f cv"ugv0"

"
C"v{r lecn'5F "f cv"ugv"ku"i tqw "qh"4F "urleg"ko ci gu"ces vktgf "d{"c"EV"qt"O TK uecppgt0' Wuwcm{ " vj gug" ctg" ces vktgf " kp" c" tgi wrct" r cwgtp" *g0 0" qpg" urleg" gxgt {" o knko gvgt+"cpf "wuwcm{ "j cxg"ctgi wrct"pwo dgt"qh"ko ci g'r kzgn"kp"ctgi wrct"r cwgtp0' Vj ku"cp"gzco r r"qh"ctgi wrct"xqno gtle" i tkf .y kj "gcej "xqno g"grgo gpv"qt"xqzgn' tgrtgugpvgf " d{"c" ukpi r" xcnw" vj cv' ku" qdvclpfg " d{" uco r rpi " vj g" ko o gf kv" ctgc" uwtqwpf kpi "vj g"xqzgn0'



Hki wtg'50" Xqno gtle'Dcugf "I tcr j lecn'Tgpfgtkpi " "

"
" Vq"tgpfgt "c"4F "r tqlgvqpp"qh"vj g"5F "f cv"ugv."qpg"htuv'pggf u"vq"f ghkg"ceco gtc"kp" ur ceg'tgrvkg'vq"vj g"xqno g0Cnuq."qpg"pggf u"vq"f ghkg'vj g"qr cekv{ "cpf "eqmt"qh'gxgt {" xqzgn0'Vj ku"ku"wuwcm{ "f ghkgf "wukpi "cp"TI DC"*hqt"tgf .i tggp."dnw."crr j c+"tcpuht" hvpvqpp"vj cv'f ghkgu'vj g"TI DC"xcnw'hqt'gxgt {"r qukdrg'xqzgn'xcnw0'

"
"
"
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"

3.1.2 Surface Based Graphical Rendering

"

Kp"5F"eqo r wgt"i tcr j leu."uwthceg"dcugf "i tcr j lecnitgpf gtlpi "cnuq"npqy "cu"r qn(i qpcn" o qf grkpi "ku"cp"cr r tqcej "hqt"o qf grkpi "qdlgeu"d{ "tgr t gugpvkpi "qt"cr r tqzko cvkpi "vj gk" uwthcegu"wukpi "r qn(i qpu0"

"

Rqn(i qpcn"o qf grkpi "ku"y gm'uwkxgf "v"uæcp" rkp"t gpf gtlpi "cpf "ku"vj gtghqtg"vj g"o gj qf " qh"ej qlæg" hqt" tgcn/vko g"eqo r wgt"i tcr j leu' Cngtpevg" o gj qf u" qh" tgr t gugpvkpi "5F" qdlgeu" kpenxf g" P WTDU" uwthcegu." uwdf kxkukqp" uwthcegu." cpf " gs wcvkqp/dcugf " tgr t gugpvkqpu" wugf "kp"tc{ "tcegtu0"

"

Vj g"dcule" qdlgev" wugf "kp"uwthceg"dcugf "t gpf gtlpi "ku" c" õxgtvgzö." c" r qlpv" kp"vj tgg" f lo gpukqpcn"ur cegu0Vy q"xgt vlegu"eqppgevgf "d{ "c"utcki j v'hkp"dgeqo g"cp"gf i g0Vj tgg" xgt vlegu."eqppgevgf "v"vj g" gcej "qvj gt" d{ "vj tgg"gf i gu."f ghkp" c" vtkcpi rg." y j lej "ku"vj g" uko r rguv"r qn(i qp"kp"Gwerkf gcp"ur ceg0O qtg"eqo r rgz"r qn(i qpu"ecp"dg"etgevgf "qw"qh" o wmkrg" vtkcpi rgu." qt" cu" c" ukpi rg" qdlgev" y kj " o qtg" vj cp" 5" xgt vlegu0' Hqwt" ukf gf" r qn(i qpu"*i gpgtcm{ "tghgttgf "v"cu"s wcf u"cpf "vtkcpi rgu"ctg"vj g"o quv"eqo o qp"uj cr g" wugf "kp"r qn(i qpcn"o qf grkpi 0C"i tqwr "qh"r qn(i qpu."eqppgevgf "v"q" gcej "qvj gt" d{ "uj ctgf " xgt vlegu."ku"i gpgtcm{ "tghgttgf "v"cu"cp"grgo gp0Gcej "qh"vj g"r qn(i qpu"o cnkpi "vr"cp" grgo gpv"ku"ecmgf "c" hceg0'

"

Vj gug" i tqwr u" qh" r qn(i qpu" y j lej " ctg" eqppgevgf " vqi gj gt" d{ " uj ctgf " xgt vlegu" ctg" tghgttgf "v"cu" c"o guj 0'Kp" qtf gt" hqt" c"o guj "v"cr r gct"cvtcevxg" y j gp"t gpf gtlpi ."k'ku" f guktcdrg"vj cv'k' dg" pqp/ugrh/kpvtugevki ." o gcplki "vj cv"pq" gf i g" r cuugu"vj tqwi j " c" r qn(i qp0"

"

Cpqvj gt" y c{ "qh" mqnkpi "cv"vj ku"ku"vj cv'vj g" o guj " ecppqv' r kgtg" kugr0' K' ku" cnuq" f guktcdrg"vj cv'vj g" o guj "pqv"eqpvkpi"cp{ "gttqtu"uwej "cu"fqwdrgf "xgt vlegu."gf i gu."qt" hcegu0Hqt'uqo g'r wtr qugu" k'ku"ko r qtvcpv'vj cv'vj g"o guj "dg" c"o cplkqrf "õ"vj cv'ku."vj cv'k' f qgu"pqv"eqpvkpi"j rrgu"qt" ukpi wrctkkgu"*nqecvqpu" y j gtg"vy q" f kulkpev"ugevqpu"qh"vj g" o guj "ctg"eqppgevgf "d{ "c"ukpi rg"xgtvgz-0'

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"

"

3.2 COLLUSION DETECTION AND METHODS

"

Eqmwukqp" f gvevqp" o gcpu" d{ "y j lej " vj g" eqo r wgt" ðnpqy uö" vj g" 5"/" f ko gpukqpcn
qtkgpvcvqp" qh" vj g" o wmk ng" qdlgeu" cpf " vj gk" tgrvcvqp" kr u" y kj " gcej " qvj gt0Eqmwukqp"
f gvevqp." y j lej " ku" cnuq" ecngf " cu" kpvgtgtpgeg" f gvevqp." emuj " f gvevqp" cpf "
kpvgtugevqp" vguvpi . "ku" wugf " hqt" f gvevpi " i gqo gvtkecn'eqpvcwu" dgwy ggp" j cr vke" f gxleg"
uv{ nuu" cpf " xkwcn'qdlgeu0]77_""

"

Eqmkukqp" f gvevqp" j cu" dggp" npqy p" hqt" c" pwo dgt" qh" { gctu0' O cp{ " t gugctej " cpf "
kpf wvukcn' hgrf u" pggf " vq" wug" k0Vj g{ " kpenmf g" tqdqvke" o qvqp" r cvj " r rcpplpi . "eqo r wgt"
i tcr j leu." i co gu" cpf " xkwcn' tgrk{ 0' Eqmkukqp" f gvevqp" ku" eqpukf gtgf " cu" c" o clqt"
dqwrgpgem' k" o cp{ " cr r rkecvqp" ctgcu0' Ugxgtcn' eqmwukqp" f gvevqp" cni qtkj o u" hqt"
qtkgpvcvqp" qh" o wmk ng" qdlgeu" j cxg" dggp" f gxgrgf . " gcej " y kj " ku" qy p" rko kcvqp"
cpf " cf xcpvcu" gu" k" eqo r wgt" i tcr j leu0' Eqmkukqp" f gvevqp" ku" c" etk' kecn' eqo r qp' gpv' qh"
j cr vke" tgp' fgtkpi 0' K' ku" pqv' r quukdrng" vq" wug" vj gug" cni qtkj o u" hqt" j cr vke" tgp' fgtkpi "
u{ uvgo u" f k' genv{ . " dgecvug" u{ uvgo u" kpenmf kpi " j cr vke" tgp' fgtkpi " pggf " hcu" cpf " ghgevxg"
eqo r wcvqp" r tqeguugu0' Vgej pls wgu" hqt" hcu" eqmkukqp" f gvevqp" ecp" dg" wugf " hqt"
ko r tqxkpi " j cr vke" tgp' fgtkpi " u{ uvgo u0"

"

Cu" o gpvqp' g" k"]77_." wukpi " eqo r wgt" i tcr j leu." eqmwukqp" f gvevqp" k" j cr vke"
tgp' fgtkpi " cni qtkj o u" ecp' vcn' g' uqo g' cf xcpvcu" gu" qh="

K Ur ceg' r ctvkvkplpi " vgej pls wgu"

KK Nqecniugctej " cr r tqcej gu"

KKK J kgtctej kecn' f cvc" utwewt gu"

"

O gj qf u" wugf " hqt" eqmkukqp" f gvevqp" ctg' emuukhgf " k" vj tgg' ecvgi qtkgu. " uwej " cu="

K Ucvke' Eqmkukqp"

KK F { pco ke' Eqmkukqp"

KKK Vko g" o' Ur ceg' Cr r tqcej "

"

k" eqmkukqp" f gvevqp." i gp' gcm{ " r qn' p' qo kcn' gs wcvqp" ctg" uqrxgf " hqt" f gvevpi " vj g"
eqmkukqp0' Vj gug' r qn' p' qo kcn' gs wcvqp" ecp" dg' emuukhgf " cu" m' ecn' cpf " i m' dcni' o gj qf u0"

"

Hktuv'o gjv qf u'ctg'uko kct"vq" "Newton's Method". Kp"vj ku"v\ r g"qh'o gjv qf u'cni qtkj o " r gthqto cpeg" tgrvxf "y kj "vj g" kpkkn' i wguu' Vj g" hqmy kpi "o gjv qf u'ctg" dcugf "qp" cni gdtcle" cr r tqcej gu" rknq" oI t³dpgt" Dcug" Cni qtkj o ö"]99]" Cnj qwi j " I t³dpgt" vgej pls wgu'ctg"umy "cpf "f q"pqv"pggf "cp { "kpkkn'i wguu."ceewtcvg"cpf "huv'cni qtkj o u" ecp"dg"f gxrqr gf "d { "tguwncpv"cpf "o ctkz"eqo r wcvkp0"

"

Eqnkukqp" f gvevqp" cni qtkj o u'ctg'f ktgew\ "tgrvxf "y kj "vj g" vgej pls wg"vq" o qf gr'xkt wcn' qdlgew" f gr gpf kpi "qp" vj g" cr r kcvkp0' Vj gtg" ctg" etkgtkpu" vq" ugrgev" vj g" o gjv qf "qh" o qf grkpi "xkt wcn' qdlgew" [5:]"

"

- Vj g"ceewtc { "vq" f kur r { "xkt wcn' qdlgew"
- Vj g"eqo r rzk\ "qh'eqnkukqp" f gvevqp" dgvy ggp" qdlgew"
- Vj g" f kkw\ "qh'o qf grkpi "f { pco k" qdlgew"
- Vj g" s wcn\ "qh'f gthqto kpi "xkt wcn' qdlgew"
- Vj g" f gvckl'qh'vj g"vqtc i g"qh'vj g" qdlgew" r tqr gt vgu"
- Vj g" equv'qh'eqo r wcvkp0"

"

Ceeqtf kpi " vq" qdlgev" o qf grkpi " o gjv qf u." eqnkukqp" f gvevqp" cni qtkj o u" ecp" dg" ercuuklf "cu="

- Uwthceg" Dcugf "Tgr t gupvkvqp"
- Xqno gtle" Dcugf "Tgr t gupvkvqp"

"

3.2.1 Collision Detection Methods in Surface Based Representation

50408'Eqpustckpvö" Dcugf "O gjv qf <"

"

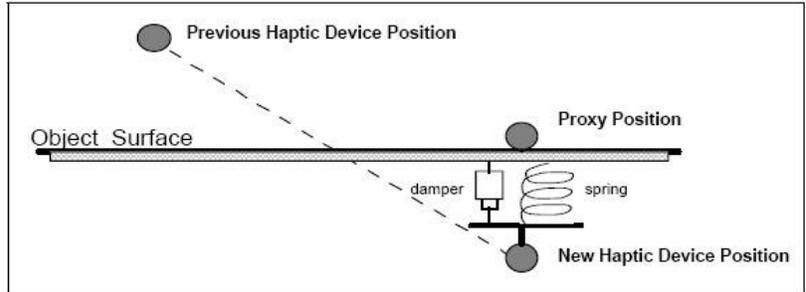
Vj ku"o gjv qf "ku"vj g"o quv'r qr wct" eqnkukqp" f gvevqp" o gjv qf "dqj "hqt" uwthceg" dcugf " cpf "xqno gtle" dcugf "tgr t gupvkvqp" kpi" j cr v\ "t gpf gt kpi 0K' wugu" r tqz { "r qkp\ kpi" qtf gt" vq" wug" j cr v\ "kpvgtcevkvqp" r qkp\ Rtqz { "ku" c" r qkp" enugn\ "hqmy u" vj g" r qukvqp" qh'vj g" j cr v\ "f gxleg']88_ " Rtqz { "r qkp" cnq" ecngf "cu" oI qf " Qdlgevö" *I Q+ " öK gcn' j cr v\ " kvgt hceg" Rqkpö" *K R+ " öUwthceg" Eqpvcev" Rqkpö" *UER+ " cpf " J cr v\ " kvgt hceg" Rqkpö"

"

*J RR-0K'tgr tguwpu'vj g'gpf "ó'r qlpv'qh'vj g'uv{ nuu'qh'vj g'j cr vle'f gxleg'cu'ugpugf "d{ "vj g" gpeqf gtu0Vj g'r qukkqp'qh'r tqz { "ku'f gvgto kpgf "d{ "Nci tcpi g'O wnk rktu0]: 8_"

Rtqz { 'r qlpv'ku'kmwutcvgf "y kj "c'ur tlpí "o qf gr0*Hi wtg'504+"

"
"



Hi wtg'504" Rtqz { "y kj "J qqnu'Ncy "kpenf lpi "Ur tlpí "Grgo gpv

"

Rtqz { "ku'cny c { u'qwukf g'qh'vj g"uwthceg0'Vj g'wr r gt"ekteng"*pco gf "óRt gxkquw"j cr vle' F gxleg'Rqukkqpö+"ku'vj g'uv{ nuu'r qukkqp" k'p'htgg'ur ceg'cpf "r tqz { "ku'xk wcn'necevkqp'qh' k0'k'p'htgg'ur ceg."y j gp"pqv'vqwej lpi "cp"qdlgev."vj g'xk wcn'cpf "r j { ukecn'r qukkqpu'qh' vj g'uv{ nuu'ctg'qxgtncr r lpi 0'Vj gtg'ku'pq'hteg"ó'hgdf dcenti gpgtcvkqp0"Y j gp"kp"eqpcev' y kj "cp"qdlgev'vj g'j cr vle'f gxleg'r qukkqp"y kni'r gpgtcvg"vj g'uwthceg"qh'vj g'uj cr g"cpf " r tqz { "y knitgo ckp"qp"vj g'qwukf g'qh'vj g'uwthceg0'Vj g'uv{ nuu'gpf "r qlpv'r gpgtcvqu'kpq" vj g'qdlgev0Dgy ggp"vj g'r tqz { "r qlpv'cpf "uv{ nuu'gpf "r qlpv." vj gtg'y knidg'f kur rnego gpv' xgevqt"cpf "hteg"ó'hgdf dcent'y knidg'i gpgtcvgf "dcugf "qp"J qqngau'ncy 0'F wtkpi "gcej " e{eng."vj ku'o gvj qf "ej gem'kh'vj g'uv{ nuu'ku'kpukf g'vj g'qdlgev0'k'vj g'f qv'r tqf wev'qh'vj g' f kur rnego gpv'xgevqt"y kj "vj g'pqto cn'qh'vj g'eqpcev'f "r tlo kxg'ku'p'gi c'kxg."vj g'uv{ nuu' ku'pqv'kpukf g'vj g'qdlgev0'Qvj gty kug."vj g'f qv'r tqf wev'ku'r qukkxg."uq"vj g'uv{ nuu'ku'uvkn' r gpgtcvki "vj g'qdlgev'cpf "vj g'r gpgtcvkqp"f gr vj "y knidg'eqo r wgf "vq'tgpf gt"vj g'hteg" ó'hgdf dcent0]32_"

"

J qqnu'ncy ="

$$F = k\Delta x \tag{3.1}$$

Y j gtg="

- k'ku'vj g'uv{ nuu'hp'gu'eqg'hteg'kp'qh'vj g'ur tlpí "

"

- Δx ku'vj g'r gpgtcevkqp'f gr vj "dgwy ggp'r tqz { 'r qlpv'cpf "pgy "j cr vle" f gxleg'r quklqp0
- "

Vj g"nyy gt "uwlhpguu"eqghhlekpv'qh'vj g"ur tkpi "i kxgu."vj g"uqlhgt"uwlhceg"vj g"wugt"hggn0 Cnuq"vj g"j ki j gt "uwlhpguu"eqghhlekpv"i kxgu="vj g"j ctf gt "uwlhceg"vj g"wugt"hggn0 Vj ku' eqghhlekpv'ku'dgwy ggp"2"cpf "3" cpf "hcti g"xcnwgu"o ki j v'ecwug'wpucdng" kpvgtcevkqp"cpf " wpf guktcdng"xkdtcevkpu0k"j92_."vj g'tgugtej gt "uclf "vj cv'oc" xctkcdng"ecp'dg'cf f gf "hqt" o qf grkpi "vj g'xgmekv { "v'kpetgcug'vj g'tgcrkv { "qh'vj g'tgpf gt kpi "wukpi "f co r gt "grgo gpv'0" "

Gs wcvkqp'dgeqo gu="

$$F = k\Delta x + b\theta \tag{3.2}$$

Y j gt g="

- b 'ku'vj g'f co r kpi "eqghhlekpv'qh'vj g"ur tkpi "
- v ku'vj g'xgmekv { 0

"

Eqputckp'gf " o" dcugf " o gyj qf " ku" nggr kpi " r quklqp" qh' vj g" uv' nnu' f wtkpi " j cr vle" kpvgtcevkqp" d { " uqtkpi " vj g" uv' nnu' r cuv' j kxqt { 0' Vj ku' o gyj qf " ku" wugf " hqt" o cp { " cr r rlecvkpu" f wtkpi " uwf lgu' Hqt" o wnk'r qlpv' eqmkukqp" f gvgevkqp" t gugtej gu" vj ku' o gyj qf "ku'wugf 0k"ej cr vgt'6."7."cpf "8."uwf lgu'cdqw'vj ku' o gyj qf "y kn'dg'i kxgp0" "

504004"K r nek'Uwlhceg'O gyj qf <"

"

Vj ku' o gyj qf " ku" ghlekpv' hqt" o qf grkpi " vj g" i gpgtci' u' cr g" qh' vj g" qdlgev' cpf " hqt" o qf grkpi " vj g" r tqrgt'vku" qh' vj g" kpu'f g" cpf " qwu'f g" qh' vj g" qdlgeu" hqt" eqmkukqp" f gvgevkqp0k"vj ku' o gyj qf . "vj g'uv' nnu'ku'tgr tgugpvgf "cu'c"ukpi ng'r qlpv="vj g'tghqtg'kv'ku'c" r qlpv'0"dcugf "kpvgtcevkqp0Vj g'gzvgtpcn'uwlhceg."y j lej "ku'ecngf "S."ecp'dg'f guetkdgf "d { " c'hwpevkqp"qh'vj g'dgny "hqt o ="

$$S(p) = 0 \tag{3.3}$$

Y j gt g="

- S 'ku'vj g'uwlhceg'qh'vj g'qdlgev'
- P 'ku'cp'ctdkct { 'hcevkqp'qh'vj g'uv' nnu'

"

"

Vj ku'o gj qf 'ku'wughwihqt's wlemn{ 'f gvevpi 'y j gj gt'vj g'uv{ nu'ku'kpukf g'qt "qwukf g'vj g" uwthceg0'k'S(p) <0.'r "ku'kpukf g'vj g'uwthceg'cpf "k'S(p) >0.'r "ku'qwukf g'vj g'uwthceg0' Cnuq'k'S(p) = 0.'r 'ku'qp'vj g'uwthceg'S0]89_"

Vj g'ko r rdek'uwthceg'o gj qf "ecp'dg'y tkwgp'cu'dgnqy 'hwpevkqp=]62_"

"

$$S = \{x, y, z \in R^3 \mid f(x, y, z) = 2\} \quad (3.4)$$

Y j gtg="

- f'ku'vj g'ko r rdek'hwpevkqp0'cnuq'ecmgf 'r qvgpvkn="
- (x,y,z)'ku'cp'ctdktct { 'r qkp'qh'vj g'uv{ nu'kp'5F 'ur ceg0'

"

Vj g'hwpevkqp'uj qy u'vj cv'vj g'ugv'qh'r qkp'w'htq'y j lej "vj g'r qvgpvkn'xcnwg'ku'gs wcn'vq" | gtq0Vj g'ko r rdek'uwthceg'hwpevkqp'ecp'uko wrcv'uwthceg'r tqr gt'kgu'gcu'k' "d{ 'vcpi gpv' vq'uwthceg'ku'ecrewcv'f0"

"

Dw'k'ku'f k'hw'w'vq'f gvgto kpg'y j lej 'r qkp'v'qp'vj g'uwthceg'uj qwf "dg'wugf 'hqt'hqteg' o' hggf dcm'tgpf g'kpi "y j gp"eqnkukqp'ku'qee'wtg'f0'Vj g'uwthceg'pqto cn'(n)'tgr t'gugpv'f " hqt'vj g'ko r rdek'uwthceg'ku'eqo r wgf 'htqo 'vj g'i tcf k'gpv'qh'vj g'ko r rdek'hwpevkqp0'*∇f +

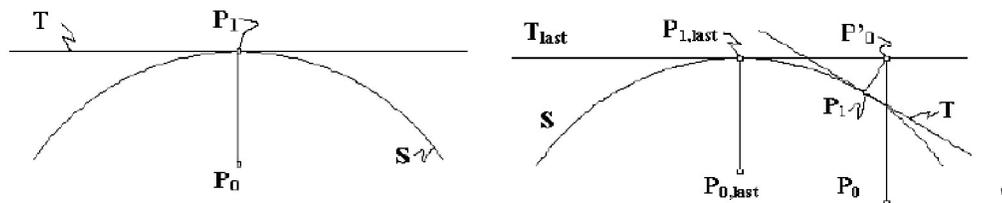
$$n = \nabla f \quad \nabla f = \left[\frac{df}{dx}, \frac{df}{dy}, \frac{df}{dz} \right] \quad (3.5)$$

"

Uo qqvj gt'uwthceg'ecp'dg'ctej kxgf "d{ " eqo r wgf 'vj g'uwthceg'pqto cn'd { "k'p'v'qr'v'kpi " vj g'i tcf k'gpv'qh'eqp'cev'r qkp'v'pgki j dqtu0"Vj ku'o gj qf "ecp'dg'uwu o ctk'gf "k'p'k' wtg" 500]89_"

"

"



"

C+F gvgto kpkpi 'vj g'Htuv'Uwthceg'Eqpvcv'Rqkp'D+Hlpf kpi 'P gzv'Uwthceg'Eqpvcv'Rqkp

"

- Vj g'cni qtkj o "vtkgu'vq'f gvgto kpg" c'r qkp'v'qp" vj g'uwthceg"qh'v'j g'uv' nmu"(P₀) vq "T"vq" f ghpg"P₁'0'
- Vq "hpf" vj g'pgzv'r quk'k'qp"qh'v'j g'uv' nmu." c"pgy "r gtr gpf k'w'ct" vq "T"ku" f tcy p"vq" f ghpg"P'₀'0'
- P gzv'v'j g'cni qtkj o "ku"rqnk'kpi "hqt" vj g'emuguv'f k'w'cpeg"htqo "P'₀"vq" vj g'uwthceg"S." P₁'0'

"

Kó r nlek'uwthceg'o gjj qf "hpf u" vj g'eqpvcv'r qkp'v'cr r tqzko cvgn(=vj gtghqtg'v'j ku"o gjj qf " ku'hcuvtg'v'j cp'v'j g'r t'g'x'k'wu"o gjj qf "v'j g'eqpvcv'r qkp'v'qh'v'j g'uv' nmu"v'j g'uwthceg'0'

"

3.2.2 Collision Detection Methods in Volume Based Representation

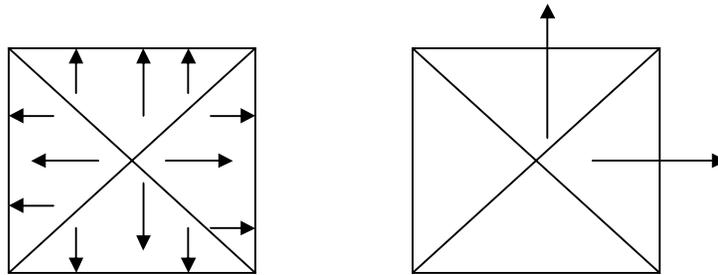
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"

"



Hli wtg'506"

Vj g'Rgpcn' 'O gjj qf ""

C+ Hqte'g'x'ge'v'qtu'r tqr qt'v'k'p'c'n'v'j g'uwthceg'f k'w'cpeg'D+Hqte'g'hggf dcerh

"

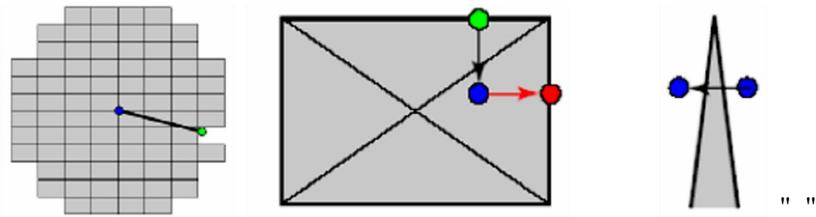
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Y j gp"vj g"uv{ nru"qh"vj g"j cr v{e" f gxleg"r gpgtcvgu"kp"vq"vj g"qdlgev."hqteg"hgdf dcent"ku" eqo r wgf "htqo "vj g"r gr vj "qh"vj g"r gpgtcvqkp0*Hki wtg"507d+"

"

"Cnj qwi j "vj g"r gpcn{ "o gjv qf "ku"vughwrlhqt"uko r ng"qdlgevu."vj gtg" ctg"rko kcvkpu"uwej " cu"hqteg"f kueqpvkpwk{ ."rceni"qh"nqecrk{ "cpf "or qr "o"vj two"qh"vj kp"qdlgevu0*Hki wtg"507e+"

"



Hki wtg"507" Vj g"Rgpcn{ "O gjv qf "Rtqdrgo u" c+"Nceni"qh"Nqecrk{ "d+"Hqteg"F kueqpvkpwk{ "e+"Rqr o"Vj tw

"

"

Vj g"r kucf xcpvc i g"qh"rceni"qh"nqecrk{ "ecwugu"vj g"r khlwrm{ "vq"r gvto kpg"y j lej "gzvgtkqt" uwhceg"uj qwf "dg"cuuqekcvf "y j gp"vj g"uv{ nru"ku"nqecv{f "cv"vj g"egpvtg"qh"vj g"qdlgev0"

Vj g"qvj gt "f kucf xcpvc i g."hqteg"f kueqpvkpwk{ ."ku"qeewttkpi "y j gp"vj g"uv{ nru"ku"etquukpi " dqwpf ctkgu"qh"vj g"qdlgev"uwd" o"xqno gu="vj g"pgctgu"gzvgtkqt"uwhceg"y km"ej cpi g"cpf " vj gtghqtg"vj g"hqteg"o ci pkwf g"cpf "f ktgevqap"y km"ej cpi g0Vj ku"i kxgu"hqteg"/"hgdf dcent" f kueqpvkpwk{ 0"Vj g"ruv"r kucf xcpvc i g." r qr "o"vj tw."ku"ecwugf "d{ "kpuwhkelpv"kpvtgpcn" xqno g"kp"vj kp"qdlgevu"vq"i gpgtcv"c" hqteg"xgevqt."uq"vj cv"vj g" uv{ nru"i qgu"vj tqwi j "vj g" uwhceg"y kj qwf i kxkpi "hqteg"o"hgdf dcent0

"

504040Dqwpf kpi "Xqno gu"O gjv qf <

"

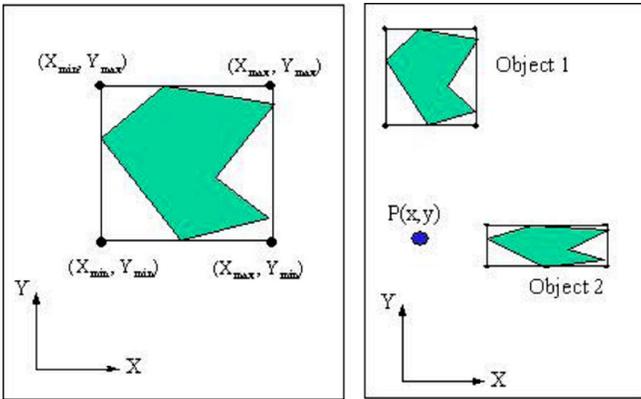
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"

"

ჰ"ჰი wtg"500l"vj g"CCDD"ნი qtkj o "ku"იკნიპი "hqt" c"ეკნიკუპ"დგუ გპ"vj g"u\ n\w" tgr tgu\pvf "d { "vj g"r qk\p"R"cpf "q dlgev3"qt "40k\vt o u"qh"eqo r wcvkqp. "k'y kn'dg"xgt { " gZR gpukxg"v"ej geni'cm"vj g"eqqt\ kpcv\q"qh'dqj "qdlgew"kp"vj g"xktwcn'gpxktqpo gpw"v" kf gp\k{ "kh" vj g" r qk\p" R" ku" k\p\kf g" gkj gt" qdlgev' Vj gtghqtg." vj g" Dqwpf kpi " xqno gu" o gj qf "eqo r wgu. hktun\ "vj g"CCDD"qh'dqj "qdlgew. "vj gp"vj g"ni qtkj o "ej genu'kh"vj g" r qk\p"R"ku" k\p\kf g" gkj gt" dqz "dghqtg" k'r tqeggf u"v" i\qecni'eqnikup" f gvgevkp0

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 d="Dcuk'F kci tco "qh"vj g"CCDD"o gj qf il'

"
"

Cu" uj qy p" cdq\g. " vj g" CCDD" v\ej pl\ w\g" f qgu" p\qv" gpenug" vj g" qdlgev" y gn0' Vj g" Qtkgp\vf "Dqwpf kpi "Dqz "ku" c" dgwgt" v\ej pl\ w\g" v" gpenug" vj g" qdlgev" \ki j v\ 0*ჰი wtg" 500l+" Vj g" cf xcp\ci gu" qh" QDD" v\ej pl\ w\g" ku" ku" ecr cd\k\k\ " hqt" tgf w\kpi " vj g" eqo r wcvkqp" \ko g" ukpeg" y j gp" vj g" u\ n\w" ku" f gvgev\ "k\p\kf g" vj g" dqwpf kpi "dqz" qh" cp" qdlgev' Vj g" u\ n\w" ku" gkj gt" xgt { "emug" v" vj g" u\w\hceg" qh" vj g" qdlgev" q\ "k\p\kf g" vj g" qdlgev." u\ "vj g" eqnikup" ecp" dg" f gvgev\ "k\p" c" hgy "kgtcvkqu=" eqpugs wgp\w\ . "vj g" equ" y kn'dg" tgf weg\ 0'k\p" cp" QDD. "vj gtg" ku" c" tgev\pi w\rt "dqz "i\qecv\g\ "cv" cp" ctdktct { "qt\kpvc\kqp" k\p" vj g" xktwcn'gpxktqpo gpw. "cpf "k'ku" vj g" j kgtcej k\cni'utwewt g" qh" vj g" u\egpg0"

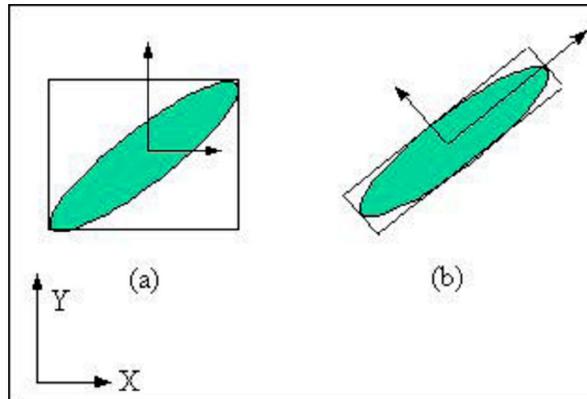
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"

o qf gnu"eqo kpi "kp"emug"r tqzko kx "vq"qvj gt "qdlgeu="vj gthqtg"kv"ku"cdng"vq" f gvgev"
 o wmkrg'eqpveu'dgy ggp"qdlgeu'y kj "c'tgo ctndng"ceewtce{0"

"
 "



Hki wtg"50" Dqwpf kpi "Xqno gu"O gjv qf "

C+Czku'Crki pgf "Dqwpf kpi "Dqz"CCDD+D+Qtkgpvf "Dqwpf kpi "Dqz"QDD+

"
 "

Kp" qtf gt "vq" f gvgev" qxgtrr " dgy ggp" y q" QDDu" kp" vj g" xkt wcn' gpxktqpo gpw. " vj ku"
 cni qtkj o "r tqlgeu"vj g"dqwpf kpi "dqz gu"qpq"uqo g"czku"kp"ur ceg'y j kej "ctg"pqv'cny c{u"
 vj g"eqqtf kpcvg"czku"Ogej "dqz"qp"vj g"czku" j cu"cp"kpvgtxcn'0'ki" QDDu"ctg"pqv'eqnkf kpi ."
 vj gug" kpvgtxcn" f q" pqv" qxgtrr . " cpf " uq" vj g" czku" ku" ecmgf " c" õugr ctcvkpi " czkuö0"
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"

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 eqo r wcvkqpu" ku" vj g" QDDVtgg" f guetkdgf" r tgxkqwan{0' Kp" }53_" kv" r tqr qugu" cp"
 ko r tqxgo gpv" qh" vj g" ghhlekpe{ " qh" vj g" dqwpf kpi " xqno gu" d{ " eqpukf gtkpi " vj g"
 pgki j dqtj qqf "eqppgevkxk{0"

"

Vj g" kf gc" ku" vq" r gthqto " c" dqwpf kpi " dqz" cpf " c" pgki j dqtj qqf " j kgtctej kecn' vtgg"
 f cvdcugu"vq" f gvgev"eqmkukqp"s wknegt0' Vj g"eqppgevkxk{ "r gthqto u"mqecn'ugctej gu"vq"
 hpf "vj g"uwdugs wgpv' eqpvev." gpcdrkpi "c"tgf wevkqp" qh" vj g" eqo r wcvkqp" vko g0' Vj g"
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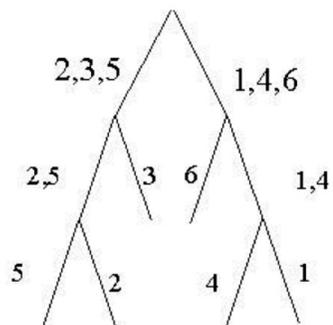
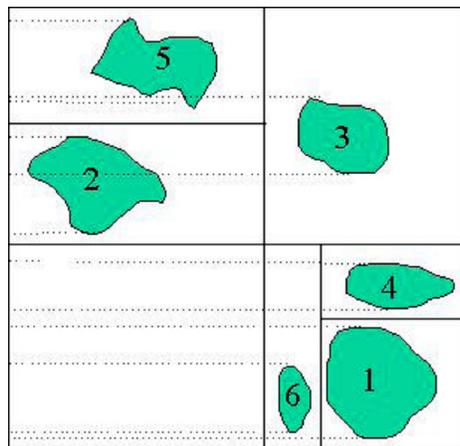
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Hki wtg'50 " Dkpt{ "Ur ceg'Rctvskqplpi " C+Rctvskqp"qh'yj g"Ur ceg'D+Dkpt{ "Ugctej "Vtgg"

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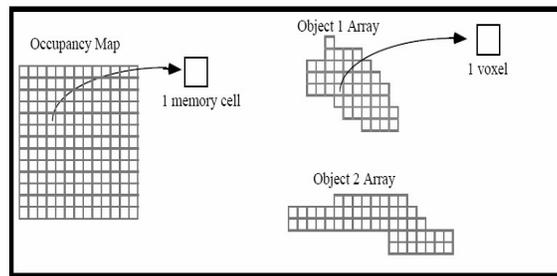
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y qtf u"xqno g'v'le"cpf "r kzgn"ku"c"xqno g"grgo gpv."tgr tgu'p'v'pi "c"xcnw"qp"c'tgi w'act"
i tkf "kp"v'j tgg"f ko gpukqpcn'ur ceg'0'Vj ku'ku'cpcni qwu"v'q"c"r kzgn"y j lej "tgr tgu'p'w"4F"
ko ci g"f c'v'0'Xqzgn'ctg"htgs w'gp'v' "wugf "kp"v'j g"xku'w'ck' c'v'k'p"cpf "cpcn' uku'qh'o gf k'cni"
cpf "uel'gp'v'k'le" f c'v'0'Uqo g't'wg"5F "f kur n' { u'wug"xqzgn'v'q" f guet'kdg'v'j gkt "t'gu'q'w'k'p'0'Hqt"
gzco r r'g."c" f kur n' { "o ki j v'dg"cdng"v'q"uj qy "734 734 734"xqzgn'0'

"

Cu"y kj "r kzgn."xqzgn'v'j go ugr'k'gu"v' r k'cni "f q"pqv'eq'v'ck'p"v'j gkt "r qu'k'k'p"kp"ur ceg"
*v'j gkt "eq'q't'f k'p'c'gu+/"dw't'c'v'j gt."k'ku'k'p'ht'g'f "dcugf "qp"v'j gkt "r qu'k'k'p"t'g'n'v'k'g"v'q"q'v'j gt"
xqzgn' "k'0' v'j gkt "r qu'k'k'p" kp" v'j g" f c'v' utw'ewt'g" v'j cv' o cng'u" w' " c" uk'p' r'g" xqno g"
ko ci g'0'Vj g'q'eer cpe{ "o cr ."y j lej "ku'cnu'q'ecmgf "xqzo cr ."ku'et'g'c'v'g'f 0'Vj g'xqzgn'cng"
r r'ceg'kp"v'j ku'o cr 0'Vj gug" xqzgn'ecp"j cxg'f k'ht'g'p'v'uk' g."qt'eq'p'w'c'p'v'uk' g'0'Qdlgeu"ctg"
tgr tgu'p'v'g'f "d{ 'xqzgn'cttc { u'kp"v'j g'xqzo cr 0]47_]48_"

"
"



Hki wtg"5Q " Xqzo cr ""

"

"

ej gemu"kh" c" xqzgn'cf f tguu'v lgu"vq" y tkg"lpv" c" xqzo cr "*"j cv'ku" crt gcf { "qeewr kgf + "d { "
vj g" xqzgn'qh' cpqj gt "qdlgeu" Vj ku" o gj qf "ku" wugf "lp" qwt "eqnkukqp" f gvevqp" cni qtkj o "
hqt "o wnk' r qkp' eqpveu"
"

504070J { dtkf "J lgtctej kecn' Tgr t gugpvcvqp" O gj qf "

Vj g" J / Eqnkf g" ku" s wkg" c" tqdwu' vgej pls wg' hqt "eqnkukqp" f gvevqp. "cpf "ku" eqo r qugf "qh"
vy q' uvr u0"
"

K' eqo r wgu" c" j { dtkf " j lgtctej kecn' tgr t gugpvcvqp" qh" qdlgeu" f wtkpi " vj g" r tg"
eqo r wcvqp" qh/ rkg. "cpf "hmqy gf "d { "cp" qp/ rkg" eqo r wcvqp 0Cv' eqo r kg" vko g" *qh/
rkg+ "ur cvkn' f geqo r qukkqp" cni qtkj o u" r ct vkkqp" vj g" xkwcn' y qtmur ceg" kp" v" eqctug/
i tclpgf "wpkhqto "i tkf "egmu" Vj gp. "c" dqwpf lpi "xqno gu" j lgtctej { "dcugf "qp" QDDVtggu"
ku" eqo r wgf "hqt" gcej "i tkf "egm' eqpvcvklpi "c" r tko kkg" qh" vj g" qdlgeu. "cpf "wug" c" j cuj "
vdrng" vq" uvtg" vj g" r qkvgt" vq" vj g" cuuqekvfg" QDDVtggu0' F wtkpi " vj g" qp/ rkg"
eqo r wcvqp. "vj g" J / Eqnkf g" cni qtkj o "kf gp vkgu" vj g" tgi kpu" qh' r qvgrvkn' eqpveu" d { "
f gvto klpki "y j lej "egmu" vj g" uv' nu" j cu" vqvej gf 0' Vj gp. "k' r cuugu" vj tqwi j "vj g" QDD/
vggu" kp" vj cv' egm' vq" f gvto kpg" kh' eqnkukqp" ku" qeewtkpi "cpf "hpcmf. "vj g" cni qtkj o "
eqo r wgu" vj g" Uwthceg" Eqpvev" Rqkv" *UER+ "vq" kf gp vkh { "vj g" gzcev' eqnkukqp" r qukkqp0'
Hico g/ vq/ Hico g' eqj gtgpeg" ku" kpvgi tcvfg "kp" vj ku" j { dtkf "cr r tqcej "vq" ecej g" vj g' eqpvev"
kphqto cvkqp" hqo " vj g" r tgxkqu" uvr " kh' vj g" nuv' vtkpi ng" *cuuwo kpi " qdlgeu" ctg"
eqo r qugf "qh" o guj "vtkpi ngu" ku" vkn' lp" eqpvev0' Vj g" f kucf xcpvi gu" qh' vj ku" o gj qf "
eqo r ctgf "vq" vj g" r tgxkqu" qpgu. "ku" vj g" kpgxkcdkxk { "qh" vj g" qh/ rkg" r tg/ eqo r wcvqp"
cpf "j ki j "uvqci g" tgs vktgo gp 0' Vj gug" f kucf xcpvi gu" o cnng" vj ku" o gj qf "vpuwkdng" hqt "
f ghqto cdrng" qdlgeu0'

"
"
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"
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"
"

eqpæw" dgy ggp" y q" qdlgeu0 k" j ku" kpvgtcevkqp." vj g" qwr w" ku" pgv" hqteg" cpf " pgv"
vts wg" cevkpi " qp" vj g" qdlgeu0"

"

4.1 3DOF HAPTIC FORCE RENDERING

"

5F QH"j cr vë" tgpf gtlpi " ku" nko ksf " vq" cr r nkecvkpu" y j gtg" r qkv" qdlgeu0 kpvgtcevkpu0F wg"
vq" ku" uko r nkekv{ . " vj ku" o gyj qf " ku" wugf " kp" j cr vë" xkuwcnk{ cvkqp" qh" f cvc" cr r nkecvkpu."
r ckpvkpi " cpf " uewr vkpi . " cpf " uqo g" o gf kecn{ cr r nkecvkpu0"

"

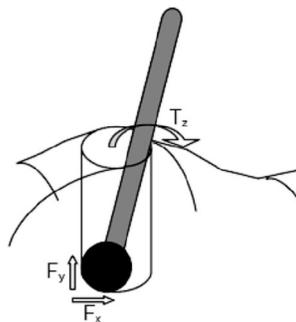
4.2 6DOF HAPTIC FORCE RENDERING

"

8" F QH"j cr vë" tgpf gtlpi " ecp" dg" cr r nkecvkpu" y j gtg" tc{ /dcugf " cpf " qdlgeu0
qdlgeu0 kpvgtcevkpu0F wg" vq" ku" vpt gutk evgf " ecr cdkkv{ . " vj ku" o gyj qf " ku" wugf " kp" cf xcpeg"
j cr vë" cr r nkecvkpu. " uvej " cu=" o gf kecn{ cr r nkecvkpu. " j ki j " tgerkuve" xkt wcn' gpxkt qpo gpvu. "
xkt wcn' cuugo drkgu. " gve0"

"

"



"

Hki vtg'60" Tc{ '6" Dcugf " J cr vë" kpvgtcevkqp" kp" 4F " J43_ "

"

"

4.3 3D MODELING & RENDERING OF DEFORMABLE OBJECTS

"

O qf grkpi " f ghqto cdng" qdlgeu0 ku" c" y gm' nppy p" eqo r wgt" i tcr j keu" uwf { 0D{ " cf f kkvq"
qh" vj g" j cr vë" hqteg" hggf dcem" f ghqto cvkqp" qh" cp" qdlgeu0 ecp" dg" hwpvkqp" qh" vj g" hqteg. "

"

eqnkukqp."ceegntc vkqp" gve0Vj g'cf f kkkqp"qh'vj g'j cr vke'hggf dcent'o cngu'vj g'f ghqto cdng"
 qdlgeu'tgrcvf'y kj "pqv'qpn' "vj g'f kgevkqp"cpf "co qwpv'qh'vj g'f ghqto cvkqp"dw'cnuq"vj g'
 f kgevkqp" cpf " o ci pkwf g" hqtegu0' O qf grkpi " f ghqto cvkqp" qh' vj g" qdlgeu" ecp" dg"
 emcuukhgf "cu" *ögeometry – based deformation modeling*ö" cpf " *öphysically – based
 deformation modeling*ö"

4.3.1 Geometry Based Deformation Modeling

"
 Kp" o cp{ " cr r kckvqpu" rkn" f guki p" vcumu." i gqo gvt { "ó" dcugf " f ghqto cvkqp" ku" wugf ."
 dgecwug"pqv'qpn' "vj g'gug"vej pls wgu"ctg"eqo r wcvkqpcmf "ghhkekp"cpf "hcuv."dw'cnuq"
 vj g' "tgn' "qp" vj g"unkm"qh' vj g'f guki pgt"tcvj gt" vj cp" qp" r j { ukecn'r tkpek rgu0' [47 _] Kp"
 i gqo gvt { "ó" dcugf " f ghqto cvkqp" o qf grkpi . " vj g" qdlgeu" ku" f ghqto gf " d { " i gqo gvtle"
 o cplr wcvkqpu0' Xgtvlegu" qt" eqpvtqn' r qlpvu" ctg" o cplr wcvgf " cpf " o qf hkgf " kp" 5"
 f ko gpukqpcn' y qtmr cegu" d { " wugt0' O cplr wcvgf " xgtvlegu" qt" eqpvtqn' r qlpvu" ctg"
 f go qpucvkpi "vj g'f ghqto cvkqp0Vy q'f khhgtgpv'v' r gu'qh'i gqo gvtle"ó"dcugf "o gj qf "ctg"
 "vertex – based""cpf ""spline – based""f ghqto cvkqp"o qf gr0'

65656 Xgtvz"ó"dcugf "F ghqto cvkqp"O qf gr<"

Kp" xgtvz"ó"dcugf " f ghqto cvkqp" o qf gr<" O cplr wcvkqp" qh' vj g" xgtvlegu" qh' vj g" xkwcn'
 qdlgev'f kur nc { u'vj g'f ghqto cvkqp"qh'vj g'xkwcn'qdlgev0F ghqto kpi "xkwcn'qdlgev'ku" f qpg"
 d { "vcpurvkpi "gcej "xgtvz"y kj kp" c"egtvc'p" f kucpeg"qh'vj g'eqnkukqp" r qlpv."cmjpi "vj g"
 f kgevkqp"kh'vj g'j cr vke'uv' nu0Vj ku" f kucpeg"ku"npqy p"cu""*the radius of influence*""; _"

Vj ku" utcki j vhty ctf " vej pls wg" ku" dcugf " qp" r qn' pqo kn' gs wcvkqp0' F ghqto cvkqp" ku"
 f gr gpf gf "qp"vj g'f gi tgg"qh'vj g'r qn' pqo kn'cpf "eqghhkekp"qh'vj g'r qn' pqo kn'0""

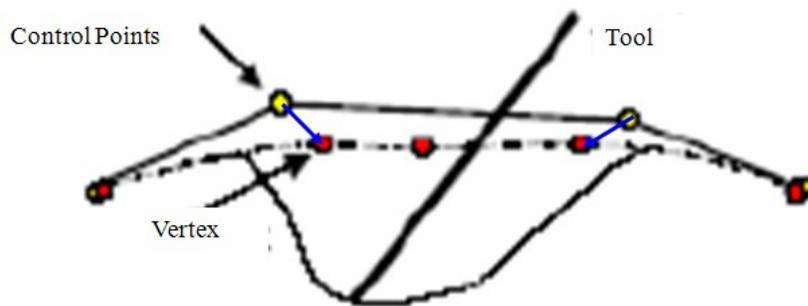
C" ugeqpf " qtf gt" r qn' pqo kn' gzc0 r ng" y kj " pq" rkpgt" f ghqto cvkqp" vgt0 " *C₁ ?2+" ku"
 uj qy p'dgmy "] ; _"

" " Vj g'F gr vj " =E₂ "+E₃ "+E₄ "*T cf kn'F kucpeg⁴ (4.1)

"Y j gtg. ""

Vj g'ewtxg'ku'ur gekhgf "o cyj go cvecmf "d{ "vj g'necvkqpu'qh'ku'hqwt'eqpvtqn'r qlpw0Vj g' ewtxg'kpgr qrcvu'vj g'eqpvtqn'r qlpw'öaö"cpf "öd . "cpf "ku'ncpi gpv'vq'vy q'qh'vj g'ukf gu'qh' vj g'eqpvtqn'r qn' i qp0O qxlpi "vj g'eqpvtqn'r qlpw'ej cpi gu'vj g'ewtxg'kp" c" r tgf levcdrng" o cppgt0

Vj g'ur rkp g"ó"dcugf "f ghqto cvkqp"o qf gr'i kxgu"hcuv'eqo r wcvkqpcn"cpf "k"ku" gcu{ "vq" ko r rgo gpv'cpf "gcu{ "vq"eqpvtqn'f ghqto cvkqp0Vj qwi j "ku"cf xcpvcu gu."vj ku"o qf gr'f qgu" pqv'uko wcv'vj g'o gej cpleu'qh'f ghqto cvkqp0



Hki wtg'60" Ur rkp g"ó"dcugf "f ghqto cvkqp"o qf gr'i]; ; "

Cp{ "r qlpv'y kj kp'vj g'ncwkeg"ecp"dg'f ghkpgf "cu="

$$Q * x . y . z += \sum_{i=2}^5 \sum_{j=2}^5 \sum_{k=2}^5 P_{ijk} B_i * x + B_j * y + B_k * z + \tag{4.3}$$

Y j gtg="

" " S " = 'DR (4.4)

" " R_m = "vj g'eqpvtqn'r qlpw"

" " D_k * z += "D₁ * { += "D_m * { += "Vj g'vj kf "f gi tgg'Dgt puvkq"r qn' ppo kcu'qt"

" " Dgl kgt "dcuku'ncwv'kqpu0"

C"o gj qf "hqt "f ktgev"o cplr wcvkqp"qh'htgg"ó"hqto "uwt hcegu"ku'ui i guvgf "d{ "J uw'gv'crl0]56_ "kp" vj ku"o gj qf . " eqpvtqn'r qlpw" ctg" o cplr wcv'gf " uwe j " vj cv" vj g' tguwv" qh' vj g' o qxgo gpv'uwt hceg'uo qqvj n{ "tgej gu'ku'kpvgpf gf "r qukkqp"d{ "c"ngcuv'us wct gu'uqnrw'kqp0

C "ukpi ng" r qlpv" qh" vj g" vj tgg" f ko gpukqpcn' qdlgev" ku" o qxgf " cp" co qwpv" qh" ΔS "" cpf " o qxgf "vq" c" pgy "hpecvkqp *Q + ΔS "+0'

Uq. "S " = "DR" ecp" dg" y tkwgp" cu" =

$$*Q + \Delta S_{3z5} = B_{3x86} *P + \Delta P_{86x5} \quad (4.5)$$

Cu" ΔP cpf ΔS ctg" vj g" ej cpi gu" kp" vj g" eqpvtqn' r qlpv" cpf " r qukkqp" qh" qdlgeu" Cdqxg" gs wcvkqp" ecp" dg" y tkwgp" cu" =

$$\Delta S_{3z5} = B_{3x86} \Delta P_{86x5} \quad (4.6)$$

Hqt" i kxgp" ΔS ecrewcvkpi " ej cpi gu" kp" vj g" eqpvtqn' r qlpv" ecp" dg" i gv" htqo " r ugwf q" kpxgtug" uqnvkqp" =

$$\Delta R = *D^V D^{+3} D^V \Delta S \quad (4.7)$$

Chgt" vj g" ej cpi gu" kp" vj g" eqpvtqn' r qlpv" ctg" npqy p. " vj g" f ghqto gf " r qukkqp" qh" vj g" xkt wcn' qdlgev" ecp" dg" ecrewcvkpi " htqo " dgny " gs wcvkqp" 0'

$$S_{pgv} = D *R + \Delta R \quad (4.8)$$

4.3.2 Physical Based Deformation Modeling

I gqo gvt { "o" dcugf " o qf gnu" hqt" o qf grkpi " f ghqto cvkqp" qh" qdlgeu" ctg" pqvt' gcrkve" Vj g { " ctg" hko kxgf " d { " gzt gtlgpeg" cpf " r cvkqpeg" qh" vj g" vugt" dgecvwug" vj g" u { uvg" " f qgu" pqv" j cxg" cp { " npqy ngf i g' cdqaw" vj g' pcwtg" qh" vj g" qdlgeu" y j lej " ku" f ghqto gf 0' k { uku" o" dcugf " f ghqto cvkqp" o qf grkpi . " vj g" hqtegu" ctg" r ctv" qh" vj g" o qvqp" cpf " f { pco leu" qh" kvgtcvcvqp" 0' Vj g" ghqtg" k' ku" pqv' pggf gf " vq" eqpukf gt " c" ugr ctcvg" eqo r wkp" i " qh" vj g" hqtegu. " dgecvwug" vj g" o qf gn' cwqo cvkcm { " eqo r wgu" vj g" o ci pkwf g" cpf " f kgecvkqp" qh" hqtegu" cr r rkgf " qp" vj g" cni' pqf gu" qh' xkt wcn' o qf gr" 0'

Vj gtg" ctg" f khtg" gpv' v { r gu" qh" r j { uku" o" dcugf " f ghqto cvkqp" o qf gn' cu" = "mass – spring model", "spring – damper model", "finite – element model", " cpf " "meshless methods" ""

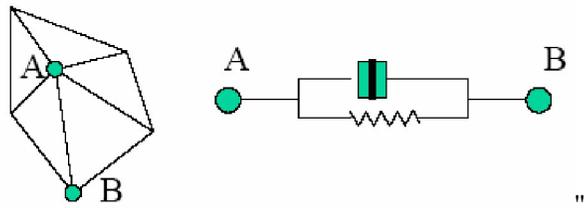
6040 O cuu'ó'Ur tkpi 'O qf gn'

"

O cuu'ó'ur tkpi 'o qf grlj cu'dggp'wugf 'y kf gn' 'cpf' gthgevkxgn('hqt'o qf grkpi 'f ghqto cdng' qdlgev'0'Kp'o cuu'ó'ur tkpi 'o qf gn' *cnuq'npqy p'cu'õParticle – Based Modelö+]; _'cp' qdlgev'ku'o qf grgf 'cu'cm'pqf gu'*xgtvz+'j cxg'o cuu'cpf 'y g{ 'ctg'eqppgevgf "v" gcej " qyj gt'y kj "c"pgwy qtn'qh'ur tkpi u'cpf 'f co r gtu'kp'c'rcwleg'utwewtg0'Vj gug'pqf gu'ctg' o qxkpi 'wpf gt'y g'kphwgepeg'qh'dqyj 'kpgtpcn'cpf 'gzvgtpcn'hqtegu'cr r rkgf "qp'yj g'xktwcn' qdlgev'0'Hki wtg'608+'"

"

"



Hki wtg'608" O cuu'ó'Ur tkpi 'O qf grl'

"

"

Kp'o cuu'ó'ur tkpi 'o qf gn'P gy vqpa'Ugeqpf 'Ncy 'i qxgtpu'yj g'o qvqp'qh'c' ukpi ng'o cuu' r qkpv'kp'yj g'rcwleg'0'

"

$$F_{total} = F_{gravitational} + F_{spring} + F_{dissipative} \tag{4.9}$$

Y j gtg=

$$F_{spring} = \sum k \Delta x \tag{4.10}$$

$$F_{gravitational} = m \cdot g \tag{4.11}$$

$$F_{dissipative} = b \cdot v \tag{4.12}$$

m ku'yj g'o cuu'qh'r qkpv'0'

x ku'yj g'r qukkqp'qh'yj g'r qkpv'0'

b ku'yj g'xgrqekv('f gr gpf gpv'f co r kpi 'hqteg'eqpuvcp'0'

k ku'yj g'r qukkqp'f gr gpf gpv'ur tkpi 'ukhpguu'eqpuvcp'0'

"

v ku'vj g'xgrmek\ "qh'vj g'xgtvz0'

g ku'vj g'i tckkcvkqpcn'ceegrctvkqp. 'k'ecp'dg'ecmgf "cu'öaö"ceegrctvkqp0'

Vj g'Gwrgt'lpvgi tcvkqp'o gjv qf "ecp'dg'wugf 'hqt'wr f cvkpi 'vj g'ceegrctvkqp.'xgrmek\ .'cpf " r qukkqp"qh'gcej "xgtvz0'Vj g'ghqtg="

"

$$\text{Acceleration of the vertex} \Rightarrow a_{t+\Delta t} = \frac{F_{total}}{m} \quad (4.13)$$

$$\text{Velocity of the vertex} \Rightarrow v_{t+\Delta t} = v_t + \Delta t a_{t+\Delta t} \quad (4.14)$$

$$\text{Position of the vertex} \Rightarrow P_{t+\Delta t} = p_t + \Delta t v_{t+\Delta t} \quad (4.15)$$

Kp"qtf gt"v"tgpfgt"uqo g"ur gekhe"r tqr gt vku"qh'qdlgev'u'eqputckp'ecp'dg'cf f gf "v"vj g" vqvrnhqteg0'K'eqputckp'u'ctg'tgpfgtgf." vj g'pgy "vqvrnhqteg"gzgtvgf "qp'vj g'qdlgev'y kni dg'f ghpfg'cu."

$$F_{total} = F_{constrained} + F_{unconstrained} \quad (4.16)$$

"

Vj gtg'ctg'f'k'htgpn'cr r tqcej gu'vj cv'ecp"ko r ngo gpv'eqputckp'gf "hqtegu0'Hqt"gzco r ng." vj g'r gpcn\ 'o gjv qf u'cpf "Nci tcpi g'o wnr rgtu'ecp'dg'wugf 'hqt'ecr'wrcv'kpi 'eqputckp'gf " hqteg0'

$$F_{constrained,i} = -k_s G^*u - k_d \partial G^*u + J \quad (4.17)$$

$G(u)$ ku'vj g'eqputcv'hwpevkp'vj cv'j cu'vq'dg'ucv'k'kf 0"

u ku'vj g'pqf cñf kur rcego gp0'

i ku'vj g'k'j "pqf g

J ku'vj g'Iceqdkp"*= $J = \frac{\partial G}{\partial u_i}$)"

Vj g'Nci tcpi g'o wnr rgtu'uqk'g'vj g'gs wcvkqp'hqt'vj g'xgevqt'Nci tcpi g'o wnr rgtu' 0'

$$JM^{-3}J^T\lambda = -\partial J \partial u - JM^{-3}F_{unconstrained} - k g - d \partial G \quad (4.18)$$

Y j gtg."M "ku'vj g'f'kci qpcn'o cuu'o cvtkz0'Vj g'eqputckp'gf 'hqteg'y kni'dg="

$$F_{constrained} = J^T\lambda \quad (4.19)"$$

"

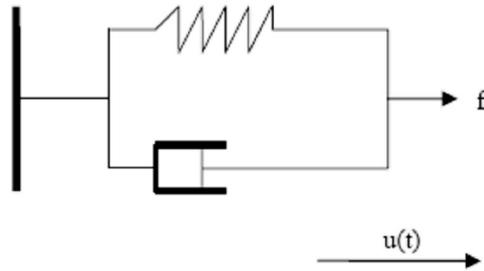
6040 Ur tkpi "F co r gt" O qf gn"

"

Vj g"ur tkpi "ó" f co r gt" o qf gn" cu" *Viscoelastic model*]92_ "ku" uko krc" vq" vj g" o cuu" ó" ur tkpi "o qf gn" dw" y kj "vj g" cf xcpvi g" qh" o qf gn" pi "vj g" gruc" o cvgtkcn" f co r lpi "dgi cxkqt0" Vj ku" o gj qf "ku" vj g" o quv" r qr wrct" o gj qf "kp" j cr v" tgpf gt lpi " u{ vgo u" f w" vq" ku" uko r rckv{ "cpf" ghkcp{ 0" Vj gt g" ctg" pwo gtqwu" r cr gtu" kp" j cr v" u" tgpf gt lpi "kvgtcw" g" vj cv" r tgu" p" v" ur tkpi "F co r gt" o qf gn" kp" j cr v" tgpf gt lpi 0]; _]33_ "]54_ "]: 6_ "Xkueqgruc" f ghqto cvkqp" ecp" dg" ko r ngo gpvgf "d{ "eqo dlp lpi "gruc" cpf " xkueqwu" r tqr gt vku0"

"

"



"

Hk wtg"60"

Ur tkpi "ó" F co r gt" O qf gn"

"

"

$$F = k\Delta x - b\dot{x} \quad (4.20)$$

"

Y j gtg="

k" ku" vj g" u" h" p" gu" eqg" h" k" cpv" qh" vj g" ur tkpi "

Δx ku" vj g" r" p" g" vt" cvkqp" f" gr" vj "dgwy" ggp" r" tqz{ "r" qkpv" cpf "p" gy" j" cr v" r" qukkqp0"

b" ku" vj g" f" co r lpi "eqg" h" k" cpv" qh" vj g" ur tkpi "

v ku" vj g" x" gmek{ 0"

"

C" ur tkpi "hqteg" ku" r tqdcdn{ "vj g" o quv" eqo o qp" hqteg" ecrcwrcv" kqp" wugf" kp" j cr v" u" tgpf gt lpi "dgecwug" k" ku" xgt{ "xgtucv" k" g" cpf "uko r r" g" vq" wug0" Vj g" ur tkpi "ku" cwcej gf" dgwy" ggp" c" hzgf" cpej qt" r qukkqp" P_o " cpf "vj g" f" gxleg" r qukkqp" P_i 0" Vj g" hzgf" cpej qt" r qukkqp" ku" wuwc{ "r r" cegf "qp" vj g" u" wt" h" ceg" qh" vj g" qdlgev" vj cv" vj g" wug" ku" v" qwej lpi 0" Vj g"

"

f kur mego gpv'xgevqt "z"? "P_o"ó" P₁"ku"uwej "y cv'v'j g"ur tkpi "hqteg"ku"cnyc {u'f kt gevgt "vqy ctf u'v'j g"hzgf "cpej qt "r qukkqp0Vj g"hqteg"hnv'ku"ecmgf "v'j g"tguvqt kpi "hqteg"qh'v'j g"ur tkpi . "ukpeg"v'j g"ur tkpi "ku"t { kpi "v'q'tguvqt g'kugrh'v'q'ku'tguv' ngpi v'j . 'y j kej "kp'v'j ku'ecug"ku"| gtq0Vj g"ukhpguu"eqpuvcpv"õk ""f levcv'j qy "ci i tguukxgn' "v'j g"ur tkpi "y km't { "v'q"tguvqt g'kugrh'v'q'ku'tguv'ngpi v'j 0Vj g"ny gt "ukhpguu"eqghlekgpv'qh'v'j g"ur tkpi "i kxgu."v'j g"uqhggt "uwt hceg"v'j g" wugt "hggnu0Cnuq"v'j g"j ki j gt "ukhpguu"eqghlekgpv"i kxgu="v'j g"j ctf gt "uwt hceg"v'j g" wugt "hggnu0Vj ku"eqghlekgpv"ku"dgwy ggp "2"cpf "3"cpf "ncti g"xcnvgu'o ki j v'ecwug"wpuvcdrg"kpvtcev'kqp"cpf "w'pf guktcdrg"xkdtcv'kpu0"

C" f co r gt" ku" cnuq" c" eqo o qp" o gcr j qt" wugf " kp" j cr vku" tgpft kpi 0' Vj g" xkueqwu" r tqr gt vku"ctg"eqpv'qmgf "d { "õbõ."v'j g" f co r kpi "eqghlekgpv'qh'v'j g"ur tkpi 0'Vj g" f co r gt" grgo gpv' ku" wugf " hqt" kpetgculpi " v'j g" tgcrlv' { "qh" tgpft kpi " d { " cf f kpi " v'j g" xgmekv' { " r ctco gvtg0' Ku" o clp" wkrkv' { "ku" hqt" tgf welpi " xkdtcv'kqp" ukpeg" kv' qrr qugu" o qv'kqp0' k'p" i gpgten" v'j g" utgpi v'j "qh" c" f co r gt" ku" r tqr qt v'kpcn' v'q" gpf "ó" ghgevt " xgmekv' { 0'Vj g" uvcpf ctf " f co r gt" gs wcv'kqp" ku" F = -bv. "y j gtg" b" ku" v'j g" f co r kpi " eqpuvcpv' / cpf " v" ku" v'j g" xgmekv' { "qh'v'j g" gpf / ghgevt 0'Vj g" hqteg" ku" cnyc { u'f q'k'v'kpi " kp'v'j g" qrr qukg' f kt gev'kqp" qh" o qv'kqp0' Vj g" u' { uvgv " ecp" dg" gzr tguugf " cu" r ctv'cn' f hgtgpv'cn' gs wcv'kqp. " RF G0' Vj g" ur tkpi " / " f co r gt" o qf gn' ecp" dg" tgr tguugv'gf " y kj " c" r ctv'cn' v'q" gcej " qv'j gt" w' q" rkgct" ur tkpi " cpf " f co r gt" w'kv'ecmgf " Xqki v'xkueqgrv'kue" o qf gn0' Hki wt g' 60+ "

60405 Hpkv'g"ó" Grgo gpv'O gvj qf "Dcuqf "O qf gn"

Hpkv'g" ó" grgo gpv' o gvj qf " dcuqf " o qf gn' ku" dcuqf " qp" f kxkf kpi " qdlgev' kp" v'q" hpkv'g" grgo gpv'0' Vj ku" o gvj qf " ku" i kxkpi " uqnv'kqp" hqt" eqo r ngz " f ghqto cdrng" qdlgevu" dgecvug" eqo r ngz " f ghqto cdrng" qdlgevu" ecppqv' dg' uqrv'gf " d { " cpcn' v'kue" o gvj qf u0' k'p" qtf gt " v'q" uwf { " y kj " eqo r ngz " f ghqto cdrng" qdlgevu. " qdlgevu" ctg' uwd " ó" f kxkf gf " kv'q" uo cm' uwd " ó" grgo gpv' lqkpv' v'qi gvj gt" d { " lqkpv' grgo gpv'0']92_ " C" hpkv'g" uwo " qh" grgo gpv' ó" ur gekhgf " kv'gtr qrv'kqp" qt' v'j cr g' h'v'p'v'kqp" i kxgu'v'j g' tguwmu' hqt' f ghqto cdrng" qdlgev'0' Vj g' v'j gqt { "qh" grv'kuekv' { "ku" v'j g" o clp" v'j gqt { " hqt" ecrew'v'kpi " pqv' qpn' { " f ghqto cv'kqp" qh'v'j g" qdlgev. " dw' cnuq' utcv'kqp" cpf " utguu' qh' gcej " pqf gu' qh' v'j g" qdlgev'0' Vj g' h'k'p'gct" utcv'kqp" cr r tqzko cv'kpu" ctg" eqo r wgf " kp" qtf gt " v'q" uko w'v'kqp" v'j g" f ghqto cv'kqp0' "

Hpkkg"grgo gpv'o gyj qf "dcugf "qp"vj g'dgrny "gs wcvkqp="

"

$$F_{*5Nx3+} = K_{*5Nx5N+} U_{*5Nx3+} \quad U_{*5Nx3+} = K_{*5Nx5N+}^{-3} F_{*5Nx3+} \quad \text{*****}(4.21)"$$

Hqt"c"5"F "qdlgev="

"

F"" ku'vj g'hqteg'xgevqt0"

K"" ku'vj g'ukhhpguu'o cvtkz0"

U"" ku'vj g'f kur mrego gpv'o cvtkz'y j lej 'i kxgu'vj g'f ghqto cvkqp'qh'qdlgev0"

N"" ku'vj g'pwo dgt'qh'vj g'pqf gu0Vj g'o wvkr rkecvkqp"d{ '5'ku'ecwugf"d{ '5'f ko gpukqp"
qh'vj g'o qf gr0"x.'y.'cpf 'z+'P qf gu'j cxg'ukhhpguu.'hqteg'cpf 'f kur mrego gpv'xcnwgu'cv'
cm'f ko gpukqp0"

" "

Hqteg'xgevqt"ku'tgrcvgf "y kj "vj g'hqteg"cr r rkgf "vq"vj g'gcej "pqf gu'qh"vj g"qdlgev0Vj g"
ukhhpguu'o cvtkz"ku"j qrf u"vj g'r tqr gtvku'qh'vj g"qdlgevu"rkmj"j qy "j ctf "qt"uqhv"vj g"wugt"
y kmhggngcej "pqf g0Hkpcmf "f kur mrego gpv'o cvtkz"j cu'vj g'uqnvkqp'qh'vj g'gs wcvkqp"cpf "
k'uko wrcvgu'j qy "wugt'y kmf gv'vj g'f ghqto cvkqp0"

"

Vj g'o ckp'f kucf xcpvc i g'qh'vj g'hpkg"grgo gpv'o gyj qf "dcugf "o qf grkpi "ku'vj g'f khheww { "
qh'vj g'o qf grkpi "hpkg"grgo gpv'o gyj qf "tqvcvqp0K'ku'f khheww"vq"i gv'c"tgcni"o"vko g"
r gthqto cpeg."cnuq"vj g"cf f kvkqp"qh"j cr vke"tgpf grkpi "vgej pls vgu"uwej "cu"hqteg"o"
hggf dcent' cpf "eqmkukqp" f gvgevkqp+"kpetgcugu"vj g"eqo r rnzkv{0' Dgecwug"qh"j gcx{ "
eqo r wcvkqp"vko g"cpf "uqrvkpi "f hhetgpvcni"gs wcvkqp"u'f kucf xcpvc i gu."hpkg"grgo gpv'
o gyj qf "ku'pqv'wughwihqt'htgg'o'hqto "eqo r wgt'ckf gf "o qf grkpi 0"

"

600406 O guj rguu'O gyj qf <"

"

Kp" o qf grkpi " f ghqto cdrng" qdlgevu." i gpgtcvqp" qh" o guj gu" ku" c" eqo r rnz" cpf "
eqo r wcvkqpcmf "rko kvgf "r tqegu0"Kp"]5: _.'vj g'o gyj qf "qh'hpkg"ur j gt gu'ku'uwf kvgf "hqt"
o qf grkpi "f ghqto cdrng"qdlgevu"y kj qw'i gpgtcvki "o guj gu0Vj ku'o gyj qf "ku'wugf "hqt"
cr r rkecvkqp'uwej "cu'r j {uleu"o"dcugf "uqhv'kuuwg'uko wrcvqp0"

"

"

"

CHAPTER 5

HAPTIC CUTTING FORCE MODELING

"

"

Vj ku'ej cr vgt "hqwugu"qp "v'g"ewwki "vqni'o qf grki "o gy qf 0'Vj g'vej pls wgu"v'tgpf gt " hqteg'o'hgfdcemly km'dg'f guetkldg'cpf "qwt'o gy qf "v'ko r ngo gpv'ewwki "o qf grki "kp" xkt wcn'gpxkqpo gpv'y km'dg'f guetkldg'f 0'

"

Kp"qtf gt "v'uko wrcv'ewwki "qr gtcvkqp."vj gtg'ctg"vy q"guugpvkn'r tqdngo u'pggf "v'dg" uqrxgf 0'HKuv'qpg'ku'vj g'ewwki "hqteg'o qf gnc'cpf "ugeqpf "qpg'ku'vj g'tgcn'vko g'f kur rc{ "qh" ewwki "qr gtcvkqp0'Vj ku'vj guku'hqwugu"qp'ewwki "hqteg'o qf grki 0'

"

5.1 CUTTING FORCE MODELLING

"

Vj g"cko "qh"ewwki "qr gtcvkqp"ku"v"tgo qxg"cur gtkkku"qp"vj g"uwtrceg"qh"vj g"kwgo " r tqeguugf "d{ "vqni"qt"o cej kpgt{0'Vj gtg'f khtgtpv'o gy qf u"wgf "kp"qtf gt "v"o qf grki ewwki "qr gtcvkqp0'Vj g{ "j cxg"uqo g"cf xcpvcu gu"cpf "f kucf xcpvcu gu0'Vj gug"o gy qf u" ecp'dg"i tqwr "kp"vj tgg"o ckp"i tqwr u="Experimental Based Cutting Force Models". "Contact Mechanics based Cutting Force Models" cpf "Proxy Based Spring Cutting Force Models"0"

"

"The experimental based cutting models" ctg"i qqf "v" f go qputcvg"vj g"ewwki "qr gtcvkqp"ht"pqp"eqo r ngz"cpf "wtcki j v'hty ctf "qr gtcvkqp0'Gzr gtko gpvcn'f cvc"vncgp" htqo "gzr gtko gpv'ctg"uqgtf"cpf "wgf"ht"ecrewrcvkp"qh"ewwki "ht"cpf "vqts wg0'Hqt" gzco r ng."kp"]37_ "vj g" rctco gvgtu"vj cv' ghge'v"vj g"ewwki "hqteg"ctg" vcdngf "d{"

"

gzt gtlk gpv" hqt" f hgt gpv" ecugu' Vj g{ " ej cpi gf" qpn{ " qpg" r ctco gvg" cpf " hz gf" " y g"
 qj gtu' kp" qtf gt" vq" ugg' ku" ghge' v' qp" eww' kpi '0' Vj g" eww' kpi " hqteg" j cu' vy q' eqo r qpgpv" = y g"
 tgukucpv" eqo r qpgpv" cpf " htle' v' kpi" eqo r qpgpv' '0' Vj g" eww' kpi " hqteg" ku" o qf gngf " y kj " c"
 f co r kpi " o ctkz" cpf " y g" v' cpur' v' kpi" xgn' ekv{ '0' Vj g" eww' kpi " ec' ew' v' g" d{ " y g"
 r ctco gvgtu" y cv' ctg" ugn' gev' g" cv' y g' dgi kpp' kpi " qh' y g" cr r' h' ec' v' kpi" h' qo " y g" v' d' r' g. " r' kng"
 u' j cr g' qh' y g' v' qqn" t' q' v' kpi" ur' ggf " g' v' '0' Vj g' r ctco gvgtu" r' kng" r' gpi y " cpf " f' gr y " qh' y g"
 eqpv' ce' v' ku" eqpv' t' qn' kpi " d{ " c' ur' gek' n' h' w' v' kpi" f' v' t' kpi " y g" cr r' h' ec' v' kpi' 0'
 "

$$F_c = F_r + F_f = mV + \mu \sim mV \sim \frac{V_{xw}}{\sim V_{xw}} = MV \quad " \quad \text{.....(5.1)"} "$$

$$F_c = K_\alpha K_\beta K_\omega K_\varepsilon \Phi * L \cdot H + MV \quad " \quad " \quad \text{..... (5.2).....} "$$

Y j gtg="

" K_α ? " y g' r ctco gvg' hqt" v' qn' luj cr g. " α ? 2. " 3. " 4i " "

" K_β ? " y g' r ctco gvg' hqt" v' k' h' p' guu' qh' v' ggy. " β ? 2. " 3. " 4i " "

" K_ω ? " y g' r ctco gvg' hqt" t' q' v' kpi" ur' ggf "

" ω ? " y g' t' q' v' kpi" ur' ggf "

" K_ε ? " y g' r ctco gvg' hqt" r' c{ gtu" qh' v' qj. " ε ? 2. " 3. " 4i " "

" $\Phi * L \cdot H +$? " y g' h' w' v' kpi" hqt" eqpv' ce' v' ctgc"

" L ? " y g' h' gpi y " hqt" eqpv' ce' v' ctgc""

" H ? " y g' f' gr y " hqt" eqpv' ce' v' ctgc" "

m " ku" y g' t' g' ukuc' peg" eqgh' h' ekpv' 0'

" V " ku" t' cpur' v' kpi" xgn' ekv{ "

μ " ku" h' tle' v' kpi" eqgh' h' ekpv'

M " ku" c" 5z5" ungy / u{ o o g' tle" o ctkz" ecngf " cu" d' f co r kpi " O ctkzö""

"

Cnj qwi j " gzt gtlk gpv" n' dcugf " o qf gni" ctg" gcu{ " cpf " h' cu" v' q" ko r r' go gpv" y g{ " j cxg"
 t' gutle' v' g" t' g' r' k{ '0' Vj g{ " ecppq" v' f go q' put' cv' g" cm" y g" ecugu" y cv' w' ugt" ecp" cr r' n{ " kp"
 r j { u' k' n' r' q' kpv' qh' x' lgy '0'"
 "

"

"Contact mechanic based models"" ctg" ceew' t' cv' g' dw' v' y g' o qf gni" qn{ " f' g' n' y' kj " r' g' th' ge' v'
 eqpv' ce' v' 0' Hqt" eqo r r' gz" eqpv' ce' v' k' ku" p' qv' r' qu' k' d' r' g" v' q" i' g' p' g' t' cv' g" p' gy " h' q' to w' r' cu" cpf "

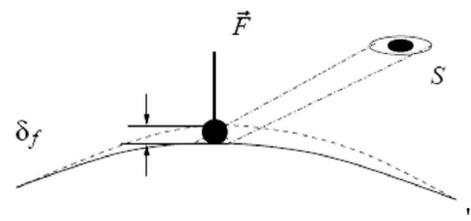
"

ecrēwrcv"j g"pgv'hqtegu0J gtv' ō"eqpcev"j gqt { "ku"wgf "hqt"j g"hqteg"o qf gnu0Grcwke"
 cpf "htkēvkpcn'hqtegu"ctg"kp f wēgf "cpf"cr r rēgf "vq"ecrēwrcv"j g"tghēvēgf "hqteg"vq"j g"
 j cr wē'tgpf gtlpi "hqt'r qn(i qpcn'o qf gnu0]3_]4_"

"
 Kp"]73_"j g"pgv'hqtegu"ctg"vcdwrcv'gf "hqt"y gni'npqy p"ur gekn'ecugu"eqpux wēgf "qp"U0'
 Xgpcpwa'r tkpek rē'y j lej "uc { u'y cv="

"
 ōKk'j g"hqtegu'cev'pi "qp"cuo cm'ctgc"qh'c"dqf { "ctg'tgr rēgf "d { "c"ucwēcm { "gs wlxcrpv"
 u{ ugo "qh'hqtegu'cev'pi "qp"j g'uco g'ctgc."j gtg'y kn'dg"eqpukf gtcdrē'ej cpi gu" kp'hqecn'
 utguu'f kwtkdwkqp."dw'y g"ghēv'cv'f kucpegu" rēti g'eqo r ctgf "y kj "j g'ctgc"qp"y j lej "
 j g'hqtegu'cev'y kn'dg"pgi rki kdrēō'

"
 "



Hki wtg'70" Cp'kpvgtcev'qp'dgy ggp'c'rēp'gct'grcwkē'dqf { "
 "

"
 Eqpukf gtlpi "j ku"ucvgo gpv'hqt"cm'v' r gu"qh'vqqr'eqpcev"qxgt"eqpcev'ctgc"S"y kj "c"
 ukpi rē'cev'pi "hqteg"H"j g'utguu'f kwtkdwkqp."cpf" eqpugs wgpw { "j g"uqtgf" grcwkē"
 gpgti { "hct"cy c { "htqo "j g'eqpcev'r rēgf."ku'cro quv'kp f gr gpf gpv'qh'j g'f kwtkdwkqp"qh"
 vcev'qp"qxgt"U."cpf"ceeqtf lpi n { "vq"j g'vqqr'uj cr g'qh'gcej "kpvgtcev'qp0"

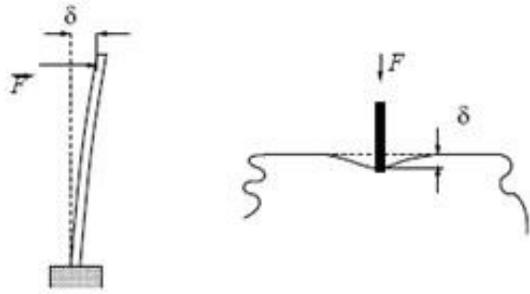
"
 Vj gtghqtg" hqt" kpvgtcev'qpu" qh' vqqr' eqpcev" qxgt" eqpcev' ctgc" S" y kj " i rēdrē'
 f ghqto cv'qp"kp"y j lej "grcwkē"gp'gti { "ku'f kwtkdwēgf "qxgt"gpv'ktg"dqf { "j g'vqcn'grcwkē"
 gpgti { "qh'j g'dqf { "f gr gpf u'qp"j g'vqqr'hqteg"crēp'g0"

"
 "
 "
 " 7:

Ecuki ncpqau'vj gqt { au'qp" f ghgevkqp" cr r nkgf "vq" kpvgtcevkpu"cv" S"y j kej "ecwug"i nqdnf
 f ghqto cvkqp" vqi gvj gt" y kj " cm quv" wplkqto " f kur mrego gpv' qxgt" U." r tgf levu" y g"
 f ghgevkqp"qh'gcej 'r qlpv'qh'U'lp"vj g'f kgevkqp"qh'vj g'vqqlhqtteg'H'vq"dg<

$$\delta_f = \frac{\partial U^* F +}{\partial F} \dots \dots \dots (5.3)$$

Y j gtg="U"ku'vj g'grcukle"gpgti { "qh'vj g" kpvgtcevkqp"0Gs wcvkqp"705"ku'cm quv'lpf gr gpf gpv'
 qh'vqqlhuj cr g="vj gt ghqtg" c' r qlpv't gr t gupcvkqp" hqt "vqqlhqtteg"ku'uwthekgp"0Hki wtg"704"
 uj qy u'cp"gzco r ng'qh'kpvgtcevkqp"y kj 'i nqdnf ghqto cvkqp0



Hki wtg"704" Ecuki ncpqau'Vj gqt {"

c+"Cp" kpvgtcevkqp"y kj 'i nqdnf ghqto cvkqp0+"Cp" kpvgtcevkqp"y kj "nqdnf gf "f ghqto cvkqp0

Vq"ugg"vj cv'vqqlhuj cr g" j cu" c"uki pkkcep'ghgevkqp"vj g" kpvgtcevkqp" hqtteg"y kj "nqdnf gf "
 f ghqto cvkqp."k'ku'uwthekgpv'vq" eqpukf gt"vj g" hqtteg/f ghgevkqp" t gur qpug"vq" c" pqto crl'
 eqpcevkqh'c"uo cmle { nqdnf tlecn'vqqlhuj cr g'y kj "cp" kpvgtcevkqp"j crh'ur ceg0]59_ "

Cu'uggp'lp"vj g'Vcdng"7 08."cm'vj g'eqpcevu'ctg'eqpukf gtgf 'r gtr gpf lewrt"vq" f ghqto cdng"
 uwthekgp0Vj ku'f kucf xcpvci g'o cmgu'vj gug"o gvj qf u'wugruu'hqt"eqo r ngz"eqpcevu0

<u>GEOMETRY</u>		<u>NORMAL FORCE F_n</u>
HNCV'J GCF "		$4RE \cdot \delta "$
URI GTG'J GCF "		$\frac{6}{5} \sqrt{RE} \cdot \delta^{5/4}$
EQPG'J GCF "		$\frac{4}{\pi} \nu p^* \alpha + E \cdot \delta^4$

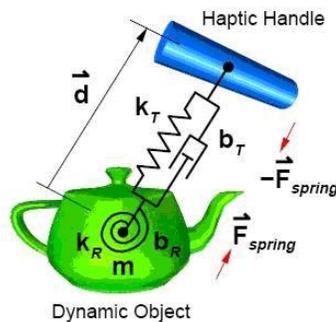
Hqteg/f ghrgv'kqp"t gur qpugu'ht' "czku/u{ o o gvtkeci'eqpcev'qh'vqqr'uj cr gu'y kj "cp" kphkpg"grcuk'e'dqf { 0'Y j gtg="

E'ku' qwpi au'o qf wmu'cpf "v'ku'Rqkuqpau'tevkq'qh'yj g'b cvgtkci'o

" R'ku'yj g'tcf kuu'qh'yj g'vqqr'vkr "cpf "alpha ku'yj g'cpi rg'qh'vqqr'vkr O'

$$E' = \frac{E}{3 - \nu^4}$$

"Proxy Based Spring Model"" ku" o qtg" ghhekgpv" hqt" eqo r rgz" eqpcev'u" f wg" vq" cf xcpvci g" qh" yj g" tgn' vko g" r j { uleci' wr f cvg" qh" yj g" f ghqto cdng" qdlge'0' Vj ku" o qf grl' y qtmu"y kj "r j { uleci'dcugf "f ghqto cvkqp" o qf grl'yj cv'ucv'gf "kp"ej cr vgt "50'Cu'ucv'gf "kp" ej cr vgt "5. "yj gtg'ctg" c'nqv'qh'uwf lgu'cdqw'yj ku" o qf grl'Uqo g'qh'yj go "ctg"ghhekgpv'cpf " uko r rg"dw"pqv" f go qpvtcvkpi "yj g"8F QH'j cr vkr "tgpf gtkpi O'kp" qtf gt"vq" wug" c"ur tkpi " dcugf "o qf grl'p'eww'kpi "qr gtcv'kqp. "yj g'o qf grl'j cu'vq" f go qpvtcv'p'qv'qpn' "yj g'tgukuc'p'v" hqteg. "dw'cnuq"t'gukuc'p'v'qts wgo' "

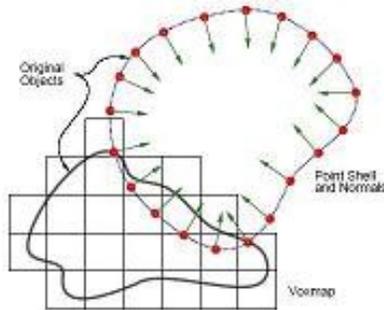


Hki vtg'70" 8F QH'Ur tkpi "o'F co r gt'O qf grl']76_"

Kp" J76_ " y g" gpxktqpo gpv' qh" ucve" qdlgew" ku" eqmgevkxgn{ " tgr tguqpvf" d{ " c" ukpi ng"
 ur cvkn' qeewr cpe{ " o cr " ecmgf " c" xqzo cr . " y j lej " ku" kmwutcvgf " kp" Hki wtg" 7060' Gcej "
 j cr vkecm{ " tgpf gtgf " htco g" lpxqixgu" uco r nkp i " y j g" xqzo cr " cv' gxtg{ " r qlpv' qh' y j g" r qlpv'
 uj gnd'

"

"



Hki wtg'706" 8F QH'Ur tkpi "o' f co r gt' O qf grif ghqto cvkqo'

"

"

Vj g'pgv' hqteg" cpf " vqts wg" cevkpi " qp" y j g" f { pco le" qdlgev' ku" qdvcvkpgf " cu" y j g" uwo " qh' cm'
 hqteg" cpf " vqts wg" eqpvt kvkqpu' htqo " uwej " r qlpv' xqz gr' lpxvtugevkqpu0'

"

Eqpegr wcm{ . " c" eqr { " qh' y j g" j cr vke" j cpf ng" ku" r megf " kp" y j g" xktwcn' uepgg" cpf " ku"
 eqwr ngf " vq" y j g" f { pco le" qdlgev' y j tqwi j " c" ur tkpi " / " f co r gt" eqppgevkq. " cu" uj qy p" kp"
 Hki wtg" 7060' Vj g' tgen' j cr vke" j cpf ng" eqpvt qni' y j g" r qukkqp" cpf " qtkgpvvkq" qh' ku" xktwcn'
 eqwpvtr ct0' Vj ku" kphwqpegu' y j g" ur tkpi au' f kur mego gpv. " y j lej " i gpgt cvgu" c" xktwcn'
 hqteg" cpf " vqts wg" qp" y j g" f { pco le" qdlgev' cpf " cp" qr r qukg' hqteg" cpf " vqts wg" qp" y j g' tgen'
 j cr vke" j cpf ng' Ur tkpi " f kur mego gpv' cnuq' kpenwf gu" tqcvkqpcn' o qvkq" d{ " y j g" ur tkcn' cv'
 y j g' egpvt " qh' y j g" f { pco le" qdlgev' Ur tkpi " hqteg' ku" r tqr qt vkqpcn' vq" f kur mego gpv. " y j kg"
 ur tkpi " vqts wg" ku" r tqr qt vkqpcn' vq" y j g" cpi ng" qh' tqcvkq" htqo " cp" gs vkxcrgpv' cpi ng"
 cpcn{ uku' cpf " f ktgevgf " cmppi " cp" gs vkxcrgpv' czku' qh' tqcvkqo'

"

Vj ku" 8F QH' ur tkpi " o cngu' y j g" f { pco le" qdlgev' vgpf " vq" ces vkt g' y j g" uco g' r qukkqp" cpf "
 qtkgpvvkq" qh' y j g" xktwcn' j cr vke" j cpf ng. " cuuwo kpi " y j cv' y j g" y q" qdlgew' ctg" kpkxcm{ "
 tgi kvgtgf " kp' uqo g' o cpgt. " g0 0' y kj " y j g' egpvt " qh' y j g" j cpf ng' mecvgf " cv' y j g" f { pco le"

"

qdlgevu'egpvt"qh'o cuu'cpf "vj g"j cpf ngau'o ckp"czku'crki pgf "y kj "qpg"qh'vj g"f { pco le"
 qdlgevu'r tkpekr cr'czgu0"

"

Vj g'hqteg"cpf "vqts wg"gs wcvkpu'wugf "j gtg"ctg<

"

$$\begin{aligned} \vec{F}_{spring} &= k_t \vec{d} + b_t \vec{v} \\ \vec{T}_{spring} &= k_R \vec{Q} + b_R \vec{\omega} \end{aligned} \quad (5.4)"$$

Y j gtg="

" k_t, b_t ? "ur tkpi "t cpur v k p c n' u k h p g u u' c p f " x k u e q u k v { "

" k_R, b_R ? "ur tkpi "t q v c v k p c n' u k h p g u u' c p f " x k u e q u k v { "

" \vec{Q} ? "gs w k x c r g p v' o " c z k u' c p i n g' " k p e n f k p i " c z k u' f k t g e v k p p - "

" $\vec{v}, \vec{\omega}$? "f { pco le" qdlgevu' t g n' v k x g' h p g c t " c p f " c p i w r c t' x g n e k v { "

"

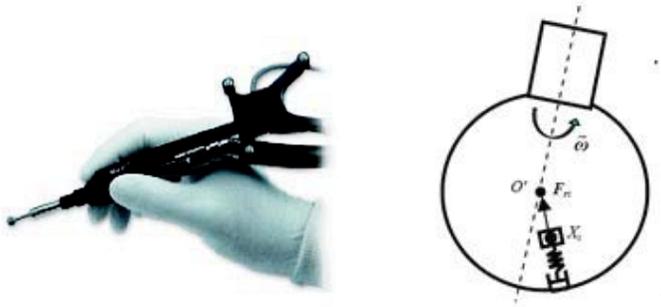
Cn j q w i j " v j k u' o g y q f " k u' w u g h w i' h q t " 8 F Q H' j c r v e " t g p f g t k p i . " v j k u' o g y q f " j c u' p q v g " k p e n f g u' e w w k p i " q r g t c v k p " c p f " f g h q t o c v k p o' k p " q t f g t " v q " w u g " v j k u' o q f g n " q p g " j c u' v q " c f c r v' k' v q " e w w k p i " q r g t c v k p u 0 "

"

k p] 5 5 _ " v j g " 8 F Q H' e w w k p i " h q t e g " o q f g r g f " w k p i " d q v j " u r t k p i " o " f c o r g t " o q f g n' c p f " v j g q t g v e c n' g s w c v k p ' h q t " v j t w u v' h q t e g' t g s w k t g f " v q' f t k n' l' c' j' q r g' q p' x q n w o g t k e' f g h q t o c d n g " d q p g " o q f g r 0 "

"

"

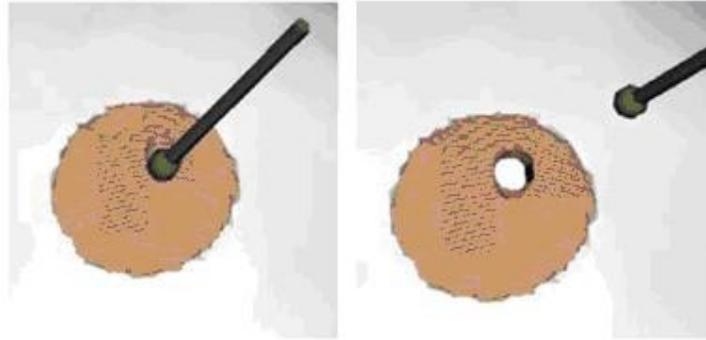


H i w g' 7 0 " T g c n' V q q n' O q f g r' c p f " U r t k p i " F c o r g t " O q f g r'] 5 5 _ "

"

"

Cnĵ qwi j "vĵ gk"o qf gr'ku'ghhlekpv'hqt "dqpg" f tkrĵpi "qr gtcvkqp." vĵ gk "f tkrĵpi "vqqr'ku" c"
 uko r rġ'tc { "dcugf "ur j gt g'j gcf gf 0" Vj ku "o qf gr'f qgu'pqv" kpenmf g'f kĥgt gpv'vĵ r gu'qh'vqqr'
 j gcf u." hlekqpcnr' ctco gvg't'cpf "vqqr'o cuu'r ctco gvg't'y j lej "ctg" ko r qtcvpv'hqt 'tgerkuo "
 qh'u{ uvg'o 0'
 "



Hki wtg'708" Tc{ "V{r g'Ur j gt g'J gcf "F tkrĵpi "Vqqr'j55_"

"
 "

5.2 OUR CUTTING FORCE MODEL

"

Chġgt "vĵ g" ewwĵpi "hġteg" o qf gr'ĵpi "hġt" j cr vĵe "tgp'f gt ĵpi "rkġgtcwtg" uwtxg{ ." vĵ g" y grn'
 npqy p'r j { ulecn'dcugf "ur tĵpi "ó" f co r gt" o qf gr'ku'f gek'f gf "vq" dg" ko r rġo gpv'gf 0" Vj gt g"
 ctg' hġu'qh' o qf gr'vĵ cv'wug'ur tĵpi " ó" f co r gt "grġo gpw'0'Y g" j cxg' kpxguk' cvgf "vĵ g" j55_"
 o qf gr'cpf "k'ku" uwkcdġ "hġt" qwt' ewwĵpi "hġteg" o qf gr'dcugo gpv'f wg" vq" ku'cf xcpwi gu0'
 Vj ku" o qf gr' ku' dcugf " qp" dqvj " ur tĵpi " ó" f co r gt" o qf gr' cpf " gzt gtko gpven' dcugf "
 gs wcvkqpu0'"

"

Vj g' ewwĵpi "hġteg" o qf gr'ĵpi "j55_" qpn{ "kpenmf gu' uqnrwkqp" hġt "ur j gt g'uj cr gf "vqqr'j gcf 0'
 Y g" ko r rġo gpv'vĵ g" hġteg" cpf "vqts wg" o qf gr'hġt "eqple" cpf "hmv'uj cr gf "vqqr'j gcf 0' kĵ"
 ur j gt g'uj cr gf "vqqr'j gcf ." vĵ g' ewwgt "ku' r gthgevn{ "u{ o o gvtlecn'lp" vĵ tgg' czgu "z. " { . "cpf " | "
 czku'0' Cnĵ ur tĵpi "/" f co r gt "u{ uvg'o w'gp'f "r qkpw" ctg' rġecv'gf "qp" vĵ g' egpv'gt "r qkp'v'qh' vĵ g"
 vqqr'0' Vj ku' ku' cp" cf xcpwi g" hġt " uko r rġecv'kqp" cpf "eqo r wcvkqp" qh' ewwĵpi "hġteg" cpf "
 vqts wg'0' Qp" vĵ g" qvj gt "j cpf ." dqvj "eqple" cpf "hmv'uj cr gf "vqqr'j gcf u' ctg" u{ o o gvtlecn'lp"
 qpn{ "y q" czgu "k" z "czku." cpf "k" { "czku" dw' pqv| "czku'0' Vj gt ghġt g" cni' vĵ g' ur tĵpi "/"
 f co r gt "u{ uvg'o w'gp'f "r qkpw" ctg' pqv' rġecv'gf "qp" vĵ g' egpv'gt "r qkp'v'qh' vĵ g' vqqr'0' Qwt' o qf gr'

"

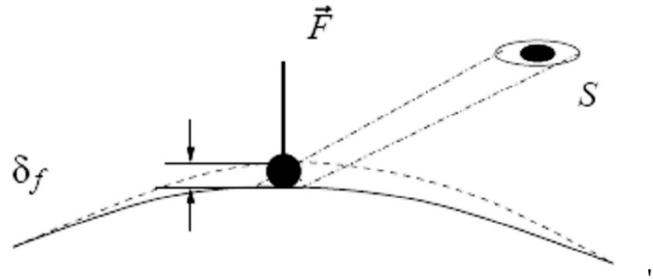
" F_{res} ku'vj g'tgukucpv'hqteg'eqo r qpgpv'

"

Kp'tgcd'y qtrf . "vj gug"y q"eqo r qpgpv'ctg"f kukt dwgf "qp"vj g"eqpvcev'uwthceg"dgwy ggp"
 vj g"ewwkp "vqqr'cpf "vj g"qdlgev'Kp"j cr vke"tgpf gtlpi . "vj g"j cr vke"fgxleg"ecp"uko wrcvg"
 r qkpv//dcugf "eqpvcev'hqteg'hggf dcen0*Hki wtg'70 +"

"

"



Hki wtg'70 " Rqkpv'Dcugf 'Eqpvcev"

"

"

Vj g'ghqtg . f kukt dwgf 'hqtegu'ctg'b qf grgf "cu'vj g{" ctg'eqpegpvcvgf "hqtegu'vj cv'cev'qp"
 vj g'egpvtg'qh'vj g"vqqr0*Hki wtg'70 +"

"

"



"

"

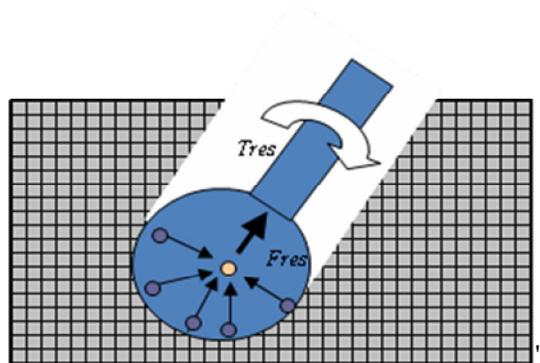
Hki wtg'70 " Vj g'F kukt dwgf "cpf 'Eqpegpvcvgf 'Tgukucpeg'Hqtegu'

"

5.2.1 Resistant Force Component

"

Vj g"tgukrcpeg"hqteg"ku"vj g"o clqt"eqo r qpgpv"qh"ewwłpi "hqteg" Vj g"tgukrcpv"hqteg" eqpukuu"qh"ur tłpi "ó" fco r gt"eqo r qpgpv"Cu"y g" f kuewuugf "łp"vj g"ej cr vgtu"6="vj g" ur tłpi "eqo r qpgpv"ku"tgrcvgf "y kj "vj g"ukłpguu"o cvgtkcn'r tqr gtv{ "qh"vj g"f ghqto cdrg" dqf {0" Vj g" fco r gt"eqo r qpgpv"ku"tgrcvgf "y kj "vj g"xkueqgrcułe"o cvgtkcn'r tqr gtv{ "qh"vj g" f ghqto cdrg"dqf {0"



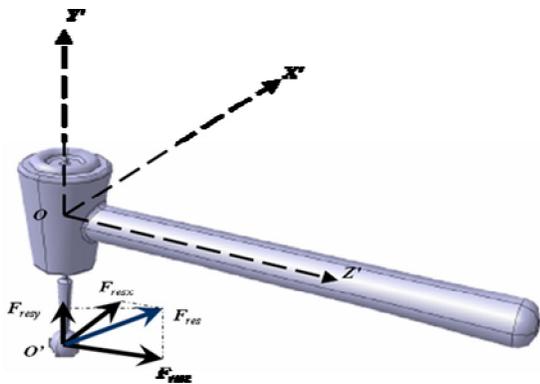
Hki wtg'702" Vj g"tgukrcpv"Eqo r qpgpv"qh"ewwłpi "łp" f ghqto cdrg"Xqzo cr"

"

"

C"ur j gtg"j gcf "vqnl"ht"tgrcułe"hqteg"cpf "vts wg"hgfdcem"ku"uj qy p"łp"Hki wtg'702" Vj g"ur j gtg"tgr tguogvgf "ht"vqnl"j gcf "ku"wuogf "vq"tgo qxg"o cvgtkcn'vj gtgd{ "hqteg"cpf " vts wg"ku"i gpgtcvgf "cpf "eqpxg{ gf "vq"wuogt0"

"



Hki wtg'703" Vj g"tgukrcpv"Eqo r qpgpv"qh"ewwłpi "

"

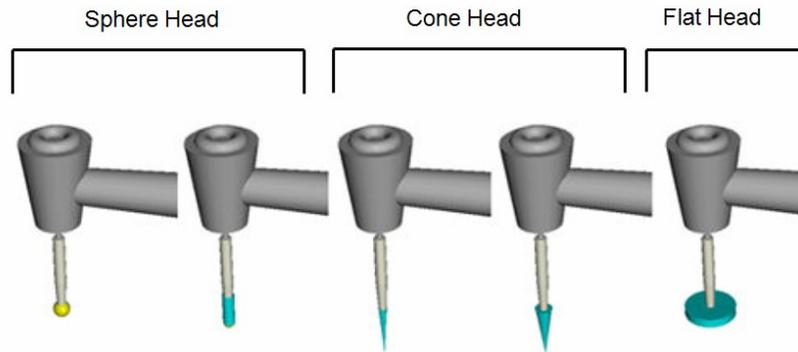
"

"

Vj g"eqo r qpgpw"qh'tgukxcpv"hqteg."F_{res}."ctg"uj qy p"lp"x."y."cpf "z"f kt ge vkqp"lp"Hki wtg"
 70300 "uj qy u'y g'egpvt"qh'y g'vqqrj gcf "cpf "O"uj qy u'y g'vr "r qkp'vqh'j cr v'e" f gxleg0'

5.2.2 Effect of Tool Shape

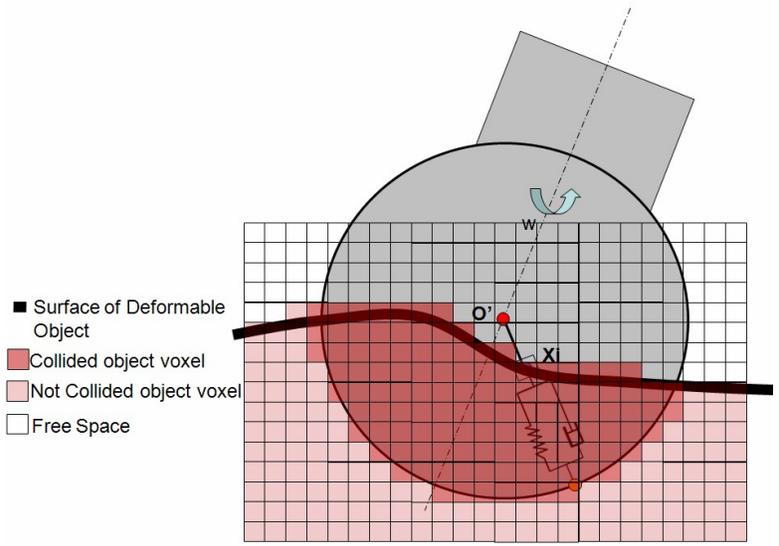
Vj gtg"ctg"f khtgpv"v{r gu"qh"vqnu."y j lej "ctg"f khtgpv"lp"uj cr gu"cpf "uk gu0'Vj gug"
 f khtgpv"v{r gu"qh"vqnu"vugf "hqt"f khtgpv"r wtr qugu"cpf "vj g{ "rgcf "v"vj g"f kxkpevkqp"qh"
 qr gtcvtu0'hgmipi "lp"qr gtcvkqp0C"f gpku'v' km' wug"f khtgpv"ewwgt"uj cr gu"v"uewr wtg"
 vj g"vgvj "ceeqt f lpi "v"f khtgpv"tgs wkt go gpw0'Vj g"uk g"cpf "ctgc"qh"vqqr'eqpcev'ecp"
 rgcf "v"gzegmgpeg"qh'y g'ewwipi "hqteg0"Cu'uj qy p"lp"Hki wtg"7034."y g'j cxg'i tqwr "vqnu"
 lp"vj tgg"o clp"i tqwr u="Urj gtg."Eqpg"cpf "Hrv"j gcf "v"etgc'v"ugxgtcn'ewwgtu"vj cv'ctg"
 wuxcm{ "wugf ."uvej "cu"ctqwpf "ewwgt."ctqwpf "gpf "e{ rkp'gt"ewwgt."c"pggf rg"ewwgt."cp"
 Z00 cu'ewwgt."cpf "c"fkue'ewwgt0'Vj g'uk g'qh'y g'ewwgt"ecp'dg'cnuq'ej cpi g0'
 "
 "



Hki wtg"7034" Vj tgg"O clp'Ewwipi "Vqqrj gcf "I tqwr u'

70408"Urj gtg"Uj cr gf "Vqqrj gcf ""

"
 F wg" vq" pcwtcn' qh" urj gtg" i gqo gt{ " cm' vj g" urtkpi " ó" f co r gt" uwd" u{ ugo u" ku"
 r gtr gpf lewrt"v"vj g'vqqr'egpvt0'Vj ku'ewwipi "j gcf "ku"vj g"uko r rg"cpf "o quv'ghlekpv"
 vqqr'uj cr g'f wg"vq"vj ku'cf xcp'ci g0'
 "
 "



Hki wtg'7085" Ur j gtkeciJ gcf 'Ewklpi "VqqnJ gcf

$$\vec{F}_{res} = \sum_i \vec{F}_{resi} = l^5 \sum_i k_i * R - \frac{\overline{OX_i}}{\overline{OX_i}} - b\vec{V}$$

$$\vec{T}_{res} = \sum_i \vec{T}_{resi} = \frac{\lambda \omega}{\pi^{4\omega}} \sum_i F_{resi} \times \omega \sqrt{\overline{OX_i}^4 - \left(\frac{\omega \cdot \overline{OX_i}}{\omega} \right)^4}$$

.....(5.6)"

Y j gtg="

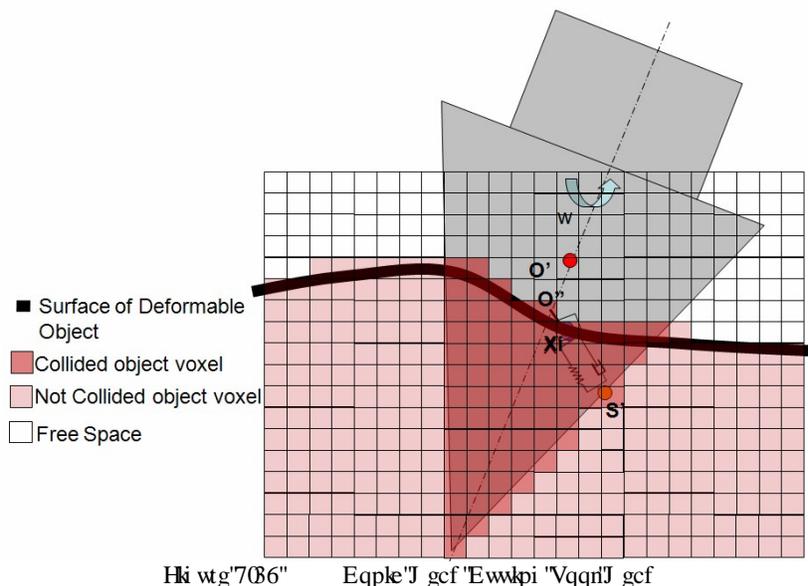
R "ku"ur j gtg"j gcf "vqqn'tcf kxu." O)"ku"vj g"ur j gtg"j gcf "vqqn'egpvgt." X_i ku"vj g"kj "xqz grn" r qukkqp0 $\overline{OX_i}$ ku"vj g"f kucpeg"htqo "egpvgt"qh"vj g"vqqn'v"kj "xqz grn0 $\frac{\overline{OX_i}}{\overline{OX_i}}$ i kxgu"vj g" hqteg"f kgevkqp0 k_i "ku"vj g"ukhpguu"eqpucpv"qh"vj g"kj "xqz grn"qh"vj g"f ghqto cdng"dqf {" cpf "l'ku"xqz grnuk g0'b ku"vj g'f co r kpi "eqghlekpv"cpf "V ku"vj g'xgrtqekv{"qh"vj g"vqqn'0w ku" vj g'dwt"cpj wct'tqvcvpi "xgrtqekv{0'l ku"c"eqpucpv0

70404'Eqple'Uj cr gf "VqqrJ gcf "

"

F wq" vq" pcwtcn' qh" eqple" i gqo gvt { . " vj g" ur tkpi " ó" fco r gt" uwd" u{ uvgu u" ku" pqv' r gtr gpf kwrct " vq" egrvtg" qh" vj g" vqqr" uq" vj g" r gtr gpf kwrct " f kwrpegu" j cxg" vq" dg" ecrwrcvgf "hqt"ur tkpi "ó" fco r gt"u{ uvgu u0'

"



"

$$\vec{F}_{res} = \sum_i \vec{F}_{resi} = l^5 \sum_i k_i \left[\frac{(S_i \cdot O)_i}{(O)_i X_i} - \frac{(O)_i X_i}{(O)_i X_i} \right] - b \vec{V}$$

$$\vec{T}_{res} = \sum_i \vec{T}_{resi} = \frac{\lambda \omega}{\omega^{4\alpha}} \sum_i \left[F_{resi} \times \omega \sqrt{\frac{(O)_i X_i}{(O)_i X_i}} - \left(\frac{\omega \cdot (O)_i X_i}{\omega} \right)^4 \right] \dots \dots \dots (5.7)$$

Y j gtg="

"

O "ku'vj g'eqple'j gcf "vqqr'egpvt. O' , ku'vj g'egpvt'hqt'r gtr gpf kwrct "f kwrpeg'hqt"eqple" uwtceg"qh'vj g"vqqr' S' i ku'vj g' uwtceg" r qkpvhqt "vj g" tgrwvgf "xqzgnr qukkqp0 Xi" ku'vj g" kj " xqzgnr qukkqp0 (O)_i X_i ku'vj g' f kwrpeg'htqo "kj " r gtr gpf kwrct "egpvt"qh'vj g" vqqr'vq' kj " xqzgnr (O)_i X_i i kxgu'vj g" hqtg "f ktgevkqp0 k_i ku'vj g' uwtceg" u'eqpucpv'qh'vj g" kj " xqzgnr

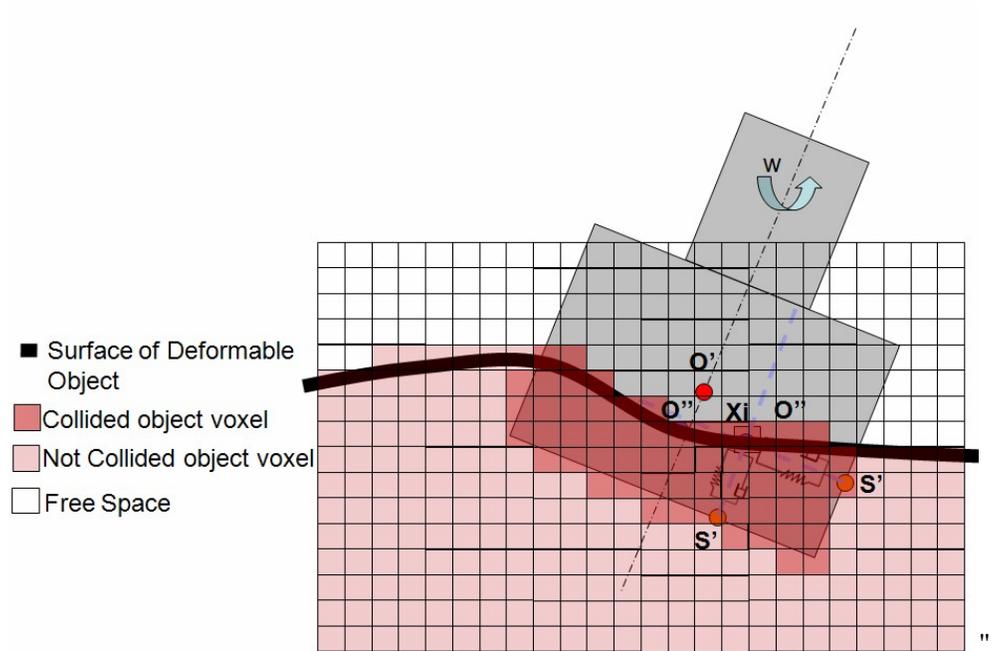
"

qh'vj g'f ghqto cdng"dqf {"cpf "l'ku"xqzgn'uk' gO'α ku'vj g"eqple"cpī ng"qh'vj g"vqqr0b"ku'vj g"
 f co r kpi "eqghlekp'v'cpf "V ku'vj g'xgn'ek'v' {"qh'vj g"vqqr0 λ ku'c"eqpu'cp'0'

70405'Hrcv'Uj cr gf "VqqrJ gcf"

F wg'v'p'cw'cn'qh'hrcv'i ggo g'gt { . 'vj g'ur tkpi "ó'f co r gt'uw'd'u'vgo u'ku'p'qv'r' gtr gpf k'ew'ct"
 v'egp'v'g'qh'vj g'vqqr'u'q'vj g'r gtr gpf k'ew'ct'f k'uc'pegu'j' cxg'v'q'dg'ec'w'w'v'g'f'hqt'ur tkpi "ó"
 f co r gt" u'vgo u'0'Vj g'g'ctg"y q" f ghqto kpi "u'w'h'cegu" qh' hrcv' vqqr'j gcf = 'vj g"ny g"
 u'w'h'cegu'cpf "vj g'uk'f g'u'w'h'cegu'0'F wg'v'q'vj g'ug'y q"gz'v'g't'p'cn'u'w'h'cegu.'vj g'ur tkpi "ó'f co r gt"
 o qf g'n'ctg'ej g'eng'f'hqt'd'qv'j'qh'vj go 0'

"
 "



Hkī wtg'7087" Hrcv'J gcf'Eww'kpi "VqqrJ gcf"

"
 "

$$\vec{F}_{res} = \sum_i \vec{F}_{resi} = l^5 \sum_i k_i \left[\frac{(S_i \cdot O)_i}{(O)_i X_i} - \frac{(O)_i X_i}{(O)_i X_i} \right] - b \vec{V}$$

$$\vec{T}_{res} = \sum_i \vec{T}_{resi} = \frac{\lambda \omega}{4\pi} \sum_i \left[F_{resi} \times \omega \left(\frac{(O)_i X_i}{\omega} - \left(\frac{\omega \cdot O)_i X_i}{\omega} \right)^4 \right) \right] \dots \dots \dots (5.8)$$

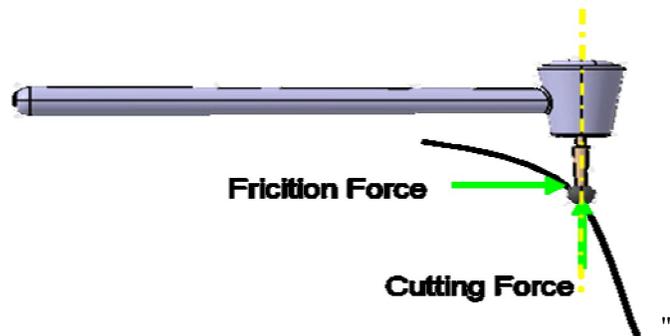
"

Y j gt g="

"
h ku'e{ rkp f tlecn'j gcf "vqqr'j gki j v."R"ku"hrv'j gcf "vqqr'tcf kwu O ""ku"vj g"hrv'j gcf "vqqr'
egpygt. O 'i ku'vj g'egpygt'hq't'r gtr gpf lewrt'f kucpeg'hq't'eqple'lwthceg'qh'vj g'vqqr'O'S'i'ku"
vj g'lwthceg'r qkpv'hq't'vj g'tgrvcgf "xqzgn'r qukvkpO'Xi'ku'vj g'kj "xqzgn'r qukvkpO')i' X' ku"
vj g'f kucpeg'htqo 'kj 'r gtr gpf lewrt'egpygt'qh'vj g'vqqr'v'kj "xqzgn'O')i' X' i kxgu'vj g'
hqteg'f kgevkpO' k' "ku"vj g"ukhpguu'eqpuwcp'qh'vj g"kj "xqzgn'qh'vj g'f ghqto cdrg'dqf { "
cpf "l'ku"xqzgn'uk'gO'α ku'vj g'eqple"cpirg'qh'vj g'vqqrO b'ku'vj g'f co r kpi "eqghlekgp'vcpf "
V ku'vj g'xgmgkv{ 'qh'vj g'vqqrO λ ku'c"eqpuwcpO'

5.2.3 Friction Force Component

"
Hlevkp'ku'vj g'hqteg'vj cv'qr r qugu'vj g'tgrvkv'g'o qvkp"qt'v'gpf gpe{ "vy ctf 'uwej 'o qvkp"
qh' vy q" lwthcegu' kp" eqpvce' Hlevkp" hqteg" ku" o cf g" w" qh" gngvtqo ci pgve" hqtegu"
dgwy ggp" cvqo uO'Y j gp"eqpvce'kpi "lwthcegu"o qxg"tgrvkv'g"v'gcej "qy'gt."vj g'hlevkp"
dgwy ggp" vj g" vy q" qdlgeu" eqpxgtu" nkpve" gpgti { " kvq" vj gto cr' gpgti { ." qt" j gcvO'
Cnj qwi j "hlevkp"hqteg"ku'pqv'c"hw'pf co gpw'nhqteg."kp"j cr v'le"t'gpf gtpi "hlevkp"hqteg"
j gr u"wg't"v'g'gg'n'vj g'xktwcn'gpxktqpo gpv'cpf "dgi c'xkt"qh'vj g'xktwcn'qdlgeu"o qtg"
tgrkv'leO'Qwt'j cr v'le"t'gpf gtpi "o qf gn'j cxg"vy q"hlevkp"ucv'g'u'v'le'kpi "cpf "urk'kpi O'
Vj g'U'le'kpi "ucv'g"o gcpu'cev'qh'lcddkpi "qt"r qnkpi "y kj "c"xktwcn'vqqrO'Vj g'urk'kpi "
ucv'g"o gcpu"o qxg'bo qqy n' "cetquu'c'lwthceg'qh'vj g'qdlge'Vj gug'v'le'kpi "cpf "urk'kpi "
ucv'g'u'ctg'cewcm' "ucv'le"cpf "f { pco le'hlevkp."t'gur gev'xgn' O'



Hki wtg'7088" Hlevkp"Hqteg"

Ucve "Hle vkqp" qeewtu"y j gp"vj g"vqpn'cpf "vj g"qdlgev'ctg"pqv'o qxlpi "tgrv'xg"vq" gcej " qvj gt. "hqt"gzco r mg="vj g"vqpn'vqvej kpi "qp" c"vqvyj 0'Vj g"eqghle kpv'qh"ucve "Hle vkqp"ku" f gpqvgf "cu" μ_s 0'Vj g" kpkkn' hqteg" vq" i gv' cp" qdlgev" o qxlpi "ku" f qo kpcvgf "d { "ucve" hle vkqp 0'Vj g"ucve "Hle vkqp"ku" j ki j gt"vj cp"vj g" f { pco le "Hle vkqp. "cu"ku"vj g"ecug'hqt'tgcn' qdlgew0

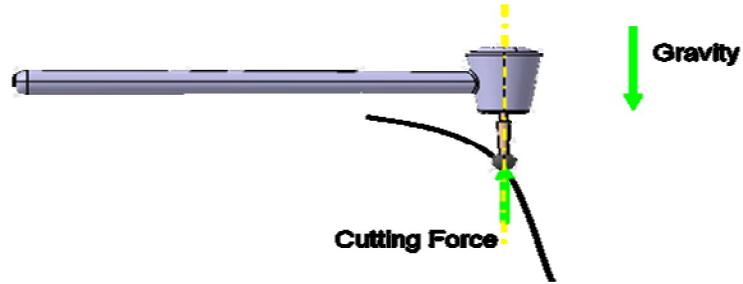
"
 F { pco le "Hle vkqp" qeewtu"y j gp"vqpn'cpf "qdlgev'ctg" o qxlpi "tgrv'xg"vq" gcej "qvj gt"cpf " twd"vqi gjv gt" *kng" c"vqpn' o qxlpi "qp" vqvyj +0'Vj g"eqghle kpv'qh" f { pco le "Hle vkqp"ku" f gpqvgf "cu" μ_D . "cpf "ku"vj cp"vj g"eqghle kpv'qh"ucve "Hle vkqp"cu" o gpvkqpgf "gctnigt 0'Vj qo " vj g" o cyj go cvkcn'r qkp"qh'xkgy. "j qy gxgt. "vj g" f khtgpeg"dgvy ggp"ucve"cpf "f { pco le " hle vkqp"ku"qh" o kpat"ko r qtcvpeg<Ngv'wu"j cxg" c"eqghle kpv'qh" hle vkqp"y j kej "f gr gpf u" qp"vj g"urkf kpi "xgrmek { "cpf "ku"wej "vj cv'ku"xcnwg"cv2" *vj g"ucve "Hle vkqp" μ_s + "ku"vj g"rko kv" qh'vj g" f { pco le "Hle vkqp" μ_D hqt "vj g" xgrmek { "vgpf kpi "vq" | gtq0"

"
 "

VCDNG'704" F { pco le ("Ucve" "Hle vkqp"

<p>$K F_t < F_s$ }" If "Ucve" "Hle vkqp" + " Hle vkqp" "Ucvg" ? " Ukenkpi " Ucvg" "" $\vec{F}_s = \mu_s \vec{F}_{RES} "$ $F_{Friction} = \vec{F}_s "$ }" Gmg" }" If "F { pco le "Hle vkqp" + " Hle vkqp" "Ucvg" ? " Urkf kpi " Ucvg" "" $\vec{F}_D = \mu_D \vec{F}_{RES} "$ $F_{Friction} = \vec{F}_D "$ " i " Gpf "K" $\vec{F}_{RES} = \vec{F}_{RES} - F_{Friction} "$ "</p>	<p>$K F_t < F_d$ }" If "Ucve" "Hle vkqp" + " Hle vkqp" "Ucvg" ? " Ukenkpi " Ucvg" "" $\vec{F}_s = \mu_s \vec{F}_{RES} "$ $F_{Friction} = \vec{F}_s "$ }" Gmg" }" If "F { pco le "Hle vkqp" + " Hle vkqp" "Ucvg" ? " Urkf kpi " Ucvg" "" $\vec{F}_D = \mu_D \vec{F}_{RES} "$ $F_{Friction} = \vec{F}_D "$ " i " Gpf "K" $\vec{F}_{RES} = \vec{F}_{RES} - F_{Friction} "$ "</p>
--	--

y gli j v0Vj ku'f ghwv'y gli j v'ku'uko kct'vq'f gpvcl'vqqu0Kp'qtf gt'vq'uj qy 'f khgt gpv'v' r gu" qh'vqqu."k'ku" i qaf "vq"j cxg'cp"qr vqpcn'i tckv' "o"vqqn'y gli j v'r ctco gvt'hqt" j cpf "cpf" g{g"eqqt f kpcvqp0'



Hki wtg'7039" I tckv' "Hqteg"

"

5.2.5 Vibration Force Component

"

Kp" cf f kklqp" vq" vj g" j cr vke" hqtegu" gxcncv'gf " f vtlpi " vj g" ewwki " qr gtcv'qp" qh" vj g" f ghqto cdng"qdlgev."k'ku"ko r qtvcpv'vq"cf f "c"uko r ng"xkdtcv'qp"ghgev'vq" kpetgcug"vj g" ngxgn'qh'tgcrkuo 0"

"

Vj g'wugt'hggnu'c"xkdtcv'qp"cnqpi "vj g'tqv'v'qp"czku" qh'vj g'ewwgt0Vj g'xkdtcv'qp"hqteg'ku" tgrcv'gf "vq"htgs wqpe{ "cpf" co r rkwf g"qh'f vtlpi "vj g"ewwki "qr gtcv'qp0'Vj g"xkdtcv'qp" hqteg'ku'gs wcn'vq="

"

$$\vec{F}_{vib} = \vec{F}_o \sin(\omega t) \quad (5.10)$$

"

Y j gtg="

" " \vec{F}_o " ku'vj g'co r rkwf g'P +"

" " f " ku'vj g'htgs wqpe{ 'J | +"

" " t " ku'vj g'vko g'tgrcv'gf "vq" kpuvcpv'pgqu'w'f cv'gf "tcv'qh'j' cr vke"

"

Qp"ewwki "qr gtcv'qpu."cnj qwi j "xkdtcv'qp"hqteg"ku"ugeqpf ct{ "v' r g"qh'hqteg"vj cv'vj g" wugt"i gu."k'j cu"cp"ghgev'qp"qxgtcm'pgv'hqteg"cpf "k'ku"ko r qtvcpv'vq"tgcej "tgcrku" ewwki 'hqtegu0'

"

5.3 TORQUE MODELLING

"
 Kp'cxlcvkqp."vj g'vj tgg'etkkekcnhki j v'f {pco leu'r ctco gvtu'ctg"tqvcvkqpu'cpi ngu'kp"vj tgg"
 f ko gpukqpu'ctqwpf "vj g'xgj leng'u'eqqtf kpcvg'u{vgo "qtki kp."vj g'egpvt"qh'o cuu0"
 "

Vj gug'cpi ngu'ctg'r keij . 'tqm'cpf "{cy <

"
Pitch "ku"tqvcvkqp"ctqwpf "vj g"nvtcn'qt" vcpuxgtug"czkuo cp"czku"twppkpi "htqo "vj g"
 r knv'u'rgn'vq"tki j v'kp'r knvgf "cketchw."cpf "r ctcmgn'vq"vj g'y kpi u'qh'c'y kpi gf "cketchw"
 vj wu'vj g'pqug'r keij gu'wr "cpf "vj g'vckif qy p."qt'xleg/xgtuc0"
 "

"
Roll "ku"tqvcvkqp"ctqwpf "vj g'npi kwf kpcn'czkuo cp"czku"ftcy p'vj tqwi j "vj g'dqf { "qh'vj g"
 xgj leng'htqo "vcki'vq"pqug"kp"vj g"pqto cn'f kgevkqp"qh'hki j v."qt"vj g'f kgevkqp"vj g'r knv'
 hcegu0Vj g"tqm'cpi ng"ku"cuq"npqy p"cu'dcpn'cpi ng"qp"c"hz gf "y kpi "cketchw"y j keij "
 \$dcpm\$'vq'ej cpi g'vj g'j qtk qpcn'f kgevkqp"qh'hki j v0"
 "

Yaw "ku"tqvcvkqp"cdqw' vj g"xgtvkn'czkuo cp"czku"ftcy p"htqo "vqr "vq"dqwqo "cpf "
 r gtr gpf lewrt "vq"vj g'qyj gt "y q'czgu0"
 "



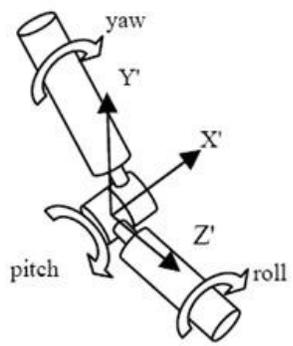
Hki wtg'708: " Cxlcvkqp'Cpi ngu'

"
 Kp'tqdqkku."cpi wrt'o qvkqpu'ctg"uwcm{ 'f guetkdgf "wukpi 'tqm'o'r keij "o" {cy "cpi ngu'cu"
 gZR nckpgf 'kp'Hki wtg'708: 0'
 "

Rkej 'tqvcgu'ctqwpf 'yj g'Z 'ó'czku0"
 [cy 'tqvcgu'ctqwpf 'yj g' ['ó'czku0"
 Tqm'tqvcgu'ctqwpf 'yj g' \ 'ó'czku0"
 "

Hqt "óNó"uj cr gf "vqpn=yj g'tqvcvqp"qh'vj g'r ke j "cpf "tqm'ku"lp"Rj cpvqo "j cr vke'f gxleg"
 ctqwpf "Z"cpf "\ "czku"j qy gxgt."yj g'tqvcvqp"qh'vj g" {cy "ku"pqv'ctqwpf "["ó"czku"cu"
 uj qy p'lp'Hki wtg'7Ø; 0"
 "

Cnuq'lp'óNó"uj cr gf "vqpn'vj g'tqvcvqp"czgu'qh'vj g'ewwlp'i "vqpn'ctg'r gthgew' { "eqkpek'f g'vq"
 j cr vke'f gxleg"uv' nnu'cv'tqm'*Z"czku+cpf "r ke j "x\ "czku+cpi rgu."dw'pqv'cv' {cy "cpi rg0"
 Vj ku'ku'cp'cpi wrct'f khtg'peg." β ,dgy ggp'vj g'ewwlp'i "vqpn'cpf "uv' nnu'uj qy p'lp'Hki wtg"
 7Ø30'
 "
 "



Hki wtg'7Ø; " J cr vke'f gxleg'cpf "Vqts wgu'

"
 "

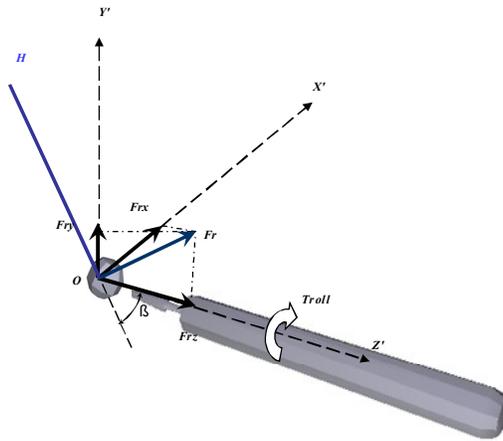
Hqt "Tc { "uj cr gf "vqpn'j cpf rg=yj g'vqts wg"qh'r ke j " T_{pitch} "cpf "yj g'vqts wg"qh' {cy " T_{yaw} "ctg"
 gs wcn'vq' | gtq0Vj g'vqts wg"qh'tqm T_{roll} "ku'gs wcn'vq="

"

$$T_{roll} = T_{res} \dots \dots \dots (5.11)$$

"

"



Hki wtg'7042" Tc{'Uj cr gf "Vqqn'cpf "Vqts wgu'

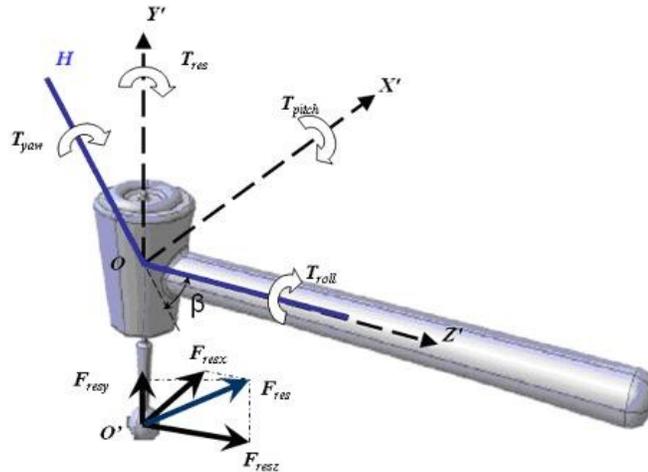
"

"

Hqt"δNö'uj cr gf "vqqn'j cpf mg="yj g"vqts wg"qh'r kej "T_{pitch}"cpf "yj g"vqts wg"qh'tqm"T_{roll}"ctg" ecrewrcvgf "y kj "hqmqy kpi "gs wcvkqpu<

"

"



Hki wtg'7043" δNö'Uj cr gf "Vqqn'cpf "Vqts wgu'

"

"

$$T_X = T_{pitch} = \left(\overrightarrow{O} \overrightarrow{O} F_{res} \cdot \overrightarrow{O} \overrightarrow{Z} \right) \overrightarrow{O} \overrightarrow{X} \quad " \quad \dots\dots\dots(5.12)"$$

Cpf."

$$T_Z = T_{roll} = \left(\overrightarrow{O} \overrightarrow{O} F_{res} \cdot \overrightarrow{O} \overrightarrow{X} \right) \overrightarrow{O} \overrightarrow{Z} \quad " \quad \dots\dots\dots(5.13)"$$

"

5.4 POWER AND MATERIAL REMOVAL

"
 O cp{ "ghqtu"j cxg"dgpp"cnpp"qp"o qf grkpi "o cvgtkcn'tgo qxcn'kp"xctkqu"o cej kpkpi "
 r tqeguugu."uwej "cu'wtpkpi ."f tkkpi ." cpf "o kkkpi 0Dw'pqv'gxgt { "f ghqto cvkqp "o qf gr'ku"
 hgcukdrg"vq'dg'wugf "hqt"j cr vkt'gpf gtpki "vj cv'hgcwtgu"t'grcvkxgn{ "j ki j "wr f cvg"tcvg0"
 "

Kp"ewwki "r tqegu."vj g" xqno g'tgo qxgf "kp"qpg'e{ eng'ku'vj g" kpvgtugevqp"qh'vj g"qdlgev"
 cpf "vj g'vqni'xqno g0Kp"j cr vkt'gpf gtpki ."j qy gxgt. "vj g'r qukkqp"qh'vj g"vqni'ku"ej gmgf "
 d{ "vj g"j cr vkt'f gxleg"kp" f kuetvg"vko g. "vj g"vko g" kpvgtxcn'ku"vj g"r gtrkf "qh'vj g"j cr vkt"
 e{ eng0"
 "

Vj g'uko r nguv'cpf "ghgcvkxg"o qf gr'tgrvgu'vj g"o cvgtkcn'tgo qxcn'vq"vj g'ewwki "r qy gt"PO"
 Rqy gt"i gpgtcvgf "f wtkpi "ewwki "qr gtcvqp"ku'gs wcn'vq="

$$P_{gen} = Torque \times Angular Speed = T \omega \quad \text{.....(5.15)}$$

"
 Y j gtg=ω ku'vj g'dwt "cpi wrt'tqcvkpi "ur ggf "qh'vj g"vqni'kp"ewwki "qr gtcvqp"cpf "vqts wg"
 ku'vj g'ewwki "vqts wg"ecrwrvgf "d{ "ewwki "hqtg0"
 "

F ghqto cdrg"qdlgev"ku'dwkn'd{ "xqzgn"cpf "r gt"gej "xqzgn"vj gtg"ku"ci"i gpgtcvgf "r qy gt"
 f wtkpi "ewwki "qr gtcvqp0Vj g"r qy gt"i gpgtcvgf "P_{gen.i}"qh"gej "xqzgn"ku'tgrvqf "vq"vj g"
 ewwki "vqts wg"Ti cevki "qp"vj cvth"xqzgn'y j gtg"cp i wrt'tqcvkpi "ku'uco g'hqt"cm'xqzgn0"
 "

$$P_{gen.i} = T_i \omega \quad \text{.....(5.16)}$$

"
 Vj gtg"ku"cnq"ci"r qy gt"tgs wktgf "P_{req} vq"tgo qxg"vj g"xqno g"qh'f ghqto cdrg"qdlgev0Vj g"
 r qy gt"tgs wktgf "P_{gen.i}"qh"gej "xqzgn"ku'tgrvqf "vq"vj g"wpk'r qy gt"tgs wktgf "vq"tgo qxg"
 vj g"o cvgtkcn'k_p"qh"kl "xqzgn0Vj g"wpk'r qy gt"tgs wktgf "ku'tgrvqf "vq"o cvgtkcn'wkhpguu"
 r tqr gtv{ 0"
 "

Ki'v' g'r qy gt "i gpgtcv'gf "r gt "gcej "xqzgn'ku"gs wcn'qt "i tgcvt "v' cv'r qy gt "tgs vktgf ."v' cp"
v' g"ith"xqzgn'ku"tgo qxgf 0'Ki'v' g'r qy gt "i gpgtcv'gf "r gt "gcej "xqzgn'ku"nguu"v' cv'r qy gt "
tgs vktgf ."v' cp"v' g"ith"xqzgn'ku"tgo kpu'0'k' qtf gt "v' "tgo qxg"v' cv'xqzgn"vugt"j cu"v' "
kpetgcug"v' g"tqcvkqp"ur ggf "qh"v' g"eww'kpi "vqn"qt "kpetgcug"v' g"eww'kpi "vts'vg" d{ "
kpetgcukpi "v' g"eww'kpi "hqtg0'v'k'kpetgcug" eww'kpi "hqtg."vugt"j cu"v' "r wuj "v' g"uv' n'w'qh"
v' g"j cr v'k'f gxleg"j ctf gt0'

"

Vj g'f ghqto cvkqp"qr gtcv'kpu"kp"i gqo gtle"fqo ckp"eqpuk'v'qh"vy q"o ckp"v'cum. "qpg"ku"
eqnkukqp" f gvgevkqp" cpf "v' g"qv' gt "ku"r qy gt "i gpgtcv'gf "hqt"o cvgtkcn"tgo qxg"ej gen0'
Dghqtg"tgo qxkpi "v' g"xqzgn."eqnkukqp" f gvgevkqp"ku"eqpf w'v'gf 0'k'v' g'ej cr v'gt "5'cpf "7."
eqmwukqp" f gvgevkqp"ku" f k'ewuugf 0'

"

"

CHAPTER 6

IMPLEMENTATION OF THE HAPTIC RENDERING SYSTEM

"

"

kp"vj ku'ej cr vgt"y g"y kni'f luewu"vj g"rdtctkgu"cpf "vj g"r tqi tco o kpi "ncpi wci g"vugf "kp" vj g"cr r rlecvkqp" f gxgnr gf "hqt"vj ku'vj guku0J ctf y ctg"cpf "uqhy ctg"eqo r qpgpw"qh'vj g" u{vgo "y kni'dg"i kxgp0Vj g"utwewt" g"cpf "vj g"hnjy ej ctv'qh'vj g"uqhy ctg"y kni'cnuq"dg" f guetkdgf 0Cv'vj g"gpf "qh'vj g"ej cr vgt"vj g"vugt "kpvgt hceg"y kni'dg"kpvtqf wegf "cpf "uqo g" uetggpuj qu'htqo "vj g"cr r rlecvkqp'y kni'dg"i kxgp0"

"

Vj g"vcun'qh"j cr ve"tgpf gtlpi "eqpuwo gu'xgt { "o wej "tgcrukve"qh'vcevkrg" hggf dcent0Qpg" qh'vj g"o clkp"kuwgu'kp"j cr ve"tgpf gtlpi "ku'vj g"cdkxk\ "vq'tgpf gt'tgcrukve" hqtegu"cpf "i kxg" vugt" vj g"tgcrukve" qh' xktwcn' gpxktqpo gpv0' Vj ku' cdkxk\ " f gr gpf u" pqv' qpn\ " qp" vj g" i gpgtcv\gf " hqteg" o qf gn' dw' cnuq" qp" vj g" ugrgevgf " ctej kgewt" g" cpf " vj g" cxckrdrg" eqo r wgt'r qy gt"*r tqeguugt-0'

"

Vj g"uqhy ctg" ctej kgewt" g" f ghkpgu" vj g" j cr ve"r tqr gt vku" vj cv'ecp" dg"tgpf gtf "kp" c" xktwcn' gpxktqpo gpv0' Vj g" j ctf y ctg" ctej kgewt" g" f kxkf gu" vj g" ugrgevgf " uqhy ctg" eqo r qpgpw"vq" f hhtgpv' eqo r wgtu" cpf " vj gtghqt" g" f ghkpgu" vj g" cxckrdrg" r tqeguukpi " r qy gt' hqt" f hhtgpv'r tqeguugu" cpf " eqo o vplecvkqp" f gr { u'dgwy ggp" vj qug'r tqeguugu0'

"

6.1 HARDWARE COMPONENTS

"
Vj g'f gf kcvgf "j cr vku'r tqeguqt "qh'qwt"j ctf y ctg'u{ uogo "ku"J R'y qtmvkvqp"zy : 422"
Zgqp"ERW'582" I J | 0'y kj "5I D"qh'TCO ."twppkpi "Y kpf qy u"ZR"qr gtcvqp"u{ uogo 0'
Qwt'f gf kcvgf "i tcr j k"ectf "ku"p xkf k'S wcf tq"HZ"6722'y kj "734'O D'i tcr j k"ectf 0"
"

C"Rj cpvqo "Rtgo kwo "30'8"F qH'j cr vku" f gxleg"cpf "c"Rj cpvqo "Qo pk'5F qH'j cr vku"
f gxleg" ctg" wugf" y kj " Qr gpJ cr vku" CRK' hqt" j cr vku" tgpf gtkpi 0' Vj gug" j ctf y ctg"
eqo r qpgvu" ctg" kpvgi tcvgf" k" UgpugI tcr j k"]52_" 5F/KY " j cr vku" ko o gtukxg"
y qtnlgpej 0'Rrgcug'ugg'Cr r gpf kz'C'hqt"j ctf y ctg'ur gekkcvkpu0'
"

"

"



Hki wtg'808" UgpugI tcr j k"5F/KY "j cr vku"ko o gtukxg"Y qtnlgpej"

"

"

6.2 SOFTWARE COMPONENTS AND ARCHITECTURE

"
Vj g"j cr vku"tgpf gtkpi "u{ uogo "j cu'vj g"hqmqy kpi "dcule"uqhy ctg"eqo r qpgvu="j cr vku"
tgpf gtgt." eqmkukqp" f gvgekvqp" cni qt kj o ." 5F " i tcr j k" tgpf gtgt." hqteg" ecrcwkvqp"
O qf gn"cpf "uvgtgqxkukqp"cpf "uqwpf "eqo r qpgvu0'
"

"

6.2.1 Haptic Renderer

"

C"j cr v'e'tgpf gtgt "etgc'vu'v'j g'j cr v'e"knwukqpu'qh'5F "qdlgev'0'K'ku'wugf 'hqt" ecrewrc'v'pi " v'j g'r qukkqp" cpf "xgnqek{ "qh' v'j g"uv{ n'u" cpf "ugpf kpi "dcem' v'j g" ecrewrc'v'gf "hqt eg" cpf " v'qts wg'hggf dcem'v'q' v'j g'wugt' v'j tqwi j "v'j g'j cr v'e" f gxleg" wugf 0'

"

Vj g" v'qmqk' hqt" j cr v'e" tgpf gtgt" r'kdtct'kgu" wugf " k'p" v'j g" v'j guku" ku" v'j g" UgpuC'drgau" Qr gpJ cr v'e'u'v'qmqk'0'Vj gtg'ctg'q'v'j gt'j cr v'e'tgpf gt'kpi "CRK'0'Vj g'dgu'hpqy "CRK'ctg" Ugpuc'drgau'gzr gpuk'g'I J QUV'CRK'97_"Ugpugl tcr j leu'ht'gg'J 5F "CRK'52_"cpf "ht'gg" qr gp'uqwt eg'EJ C'KSF "]38_0C'nj qwi j "cm'v'j gug'CRK'" j cxg'cf xcp'vci gu."cm'qh'v'j go "f q" ppq'v'ur r qtv'o wnk'eqpvcev'f gvge'v'kp" { g'0" C'm'wugu" Qr gpJ cr v'e'u'CRK'k'p" dcem'i tqwpf " hqt'eqpvt'qm'kpi 'j cr v'e" f gxleg'0'Vj g'EJ C'KSF "CRK'ku'v'gugf 'hqt' u'qo g'j cr v'e" cr r r'lec'v'kpu" cpf "k'ku'hr'gz'kdr'g'cpf "wughw'ihqt'p'gy "cni qt'k'j o u'f wg'v'q'qr gp'uqwt eg'ut wewt'g'0'

"

Qr gpJ cr v'e'u'ku'cp" qdlgev'0" qtl'gp'v'gf "5F" j cr v'e" v'qmqk' wugf " y kj "Rj cp'v'qo " j cr v'e" f gxlegu'v'j cv'gpc'drgu'f gxgnr'gtu'v'q'cf f'j cr v'e'u'v'q' v'j g'cr r r'lec'v'kpu'0'97_"Vj g'v'qmqk' ku" r cv'gt'p'gf "ch'gt'v'j g"Qr gpI N'i "CRK"o cm'kpi "k'hco k'kct"v'q"i tcr j leu'r tqi tco o gtu"cpf " h'cek'k'v'kpi "k'p'v'gi t'cv'k'p'y kj "Qr gpI N'cr r r'lec'v'kpu'0"

"

Vj g" Qr gpJ cr v'e'u' v'qmqk' k'pen'f'gu" v'j g" J cr v'e" F gxleg" CRK' *J F CRK' " v'j g" J cr v'e" N'kdtct { "CRK'*J NCRK'0'95_"96_0'Vj g'J F CRK'r tqx'kf'gu'hty /rgxgn'ceegu'v'q'v'j g'j cr v'e" f gxleg."gpc'drgu" j cr v'e'u'r tqi tco o gtu"v'q"tgp'f'gt" hqt'egu'f k'ge'v'f . "q'lh'gtu" eqpvt'q'i'q'x'gt" eqp'hi w'kpi " v'j g" tw'p'v'ko g" dgj cx'k'qt " qh' v'j g" f tk'x'gtu." cpf " r tqx'kf'gu" eqp'x'gp'k'gp'v' w'k'k'v' { " hgc'wt'gu"cpf "f g'dwi i kpi "ck'f u'0'Vj g'J NCRK'r tqx'kf'gu'j ki j /rgxgn'j cr v'e'tgpf gt'kpi "cpf "ku" f gu'ki p'gf "v'q"dg" h'co k'kct"v'q"Qr gpI N'CRK'r tqi tco o gtu'0'K'cm'qy u"uki p'k'k'ec'p'v'tgwug'qh' Qr gpI N'eq'f'g" cpf "i tgc'v'f "uk'o r r'k'k'gu"u{ pe'j tq'p'k' cv'k'p"qh' v'j g" j cr v'e'u"cpf "i tcr j leu" v'j t'gcf u'0"

"

Cu" f guet'k'dgf "k'p"96_"Vj g"J NCRK'hq'm'qy u"i tcr j leu"v'ge'j p'ks w'gu" v'j qug" h'q'w'p'f "k'p"v'j g" Qr gpI N'CRK'0'K'ku'cp" gcu{ "r tq'egu'v'q"cf f'j cr v'e"v'j cv't'gugo dr'gu"v'j g'o qf g'n'wugf "v'q" tgr t'gug'p'v'j g'qdlgev'i tcr j k'ecm' { 0'U'k'k'p'guu'cpf "ht'k'v'k'p"r tqr gt'v'gu'qh'o cv'gt'k'cu"ec'p'dg" j cpf r'gf "g'cu'k' { "w'k'p'i "J NCRK'0'Vj g'J NCRK'cu'q"r tqx'kf'gu" gx'gp'v'j cpf r'kpi "hqt" gcug'qh' k'p'v'gi t'cv'k'p'k'p'v'q'cr r r'lec'v'kpu'0"

"

Vj g"J F CRKku'dguf'uwkxgf 'hqt'f gxgnr gtu'y j q'ctg'fco kkt'y kj " j cr vkr'tqi tco o kpi " cpf "ugpf kpi "hqtegu'f kgev' 0'Vj ku'kpenf gu'vj qug"kpvtgugf "kp"j cr vku'tgugtej "cpf " tgo qvg'o cpr wvkvpu0"

"

K'ku'r quukng"v"wg"vj gug"y q"CRK'kp"eqplwpevkp"v"vng"cf xcpwi g"qh'dqvj "UF Mu" hqt "gzi gtvf gxgnr gtu0Vj g"J NCRKku'dwkn"qp"vqr "qh'vj g"J F CRK'kr tqxf gu'c'j ki j gt " ngxgn'eqvtqri'qh'j cr vku'vj cp"J F CRK0"

"

Kp"qwt" cr r dekvpk. "k'ku" tgs wktgf "v" o cpci g"fkgev' hqtg" tgpfgtkpi "hqt" vj g"j cr vkr " f gxleg"kp"J F CRK'y j gtgcu"J NCRK'j cpf ngu"vj g"i tcr j leu'cpf " r qkp' dcugf "eqnkup0" Hqtg" tgpfgtkpi "y kj "J F CRK'tgs wktgf"ghh'ekpv'hqtg" tgpfgtkpi . "eqnkup" f gvgevkp" cni qtkj o u'cpf "f cv" utwewtgu0Vj ku'ku'f wg"v"vj g"j ki j "htgswpe{ "qh'hqtg" tgh'gij gu" tgs wktgf 'hqt'ucdng'emugf /mqqr "eqvtqri'qh'vj g'j cr vkr "f gxleg0' J NCRK'gpcdngu'cp'gxgpv" f tkxp'r tqi tco o kpi "o qf gn"y j lej "gcugu"vj g"ko r ngo gpv'vkp"qh'eqo r dekvgf "j cr vkr " kpvtcev'kpu'kpxqikpi "gxgpv'rkng"vqwej kpi "i gqo gvt { . "dwwqp"enkem. "cpf "o qv'kpo0"

"

6.2.2 Collision Detection Algorithm

"

Vj g"r wtr qug" qh' vj g" eqnkup" f gvgevkp" cni qtkj o " ku" v" i kxg" kphqto cvkpp" qp" cni' eqnkuppu" dgw ggp" xkt wcn' qdlgeu0' Dcugf " qp" vj ku' kphqto cvkpp" vj g" qdlgeu" o qv'kpp" uj qwf "dg'eqpvtckpgf "uq'vj cv'qdlgeu"uj qwf "pqv'dg'cdng"v"r cuu'vj tqwi j "gcej "qvj gt0C" rnen'qh'ghh'ekgpe{ "kp"vj g"eqnkup" f gvgevkp" cni qtkj o "o c{ "dg" c" dqwrgpgeni'kp"j cr vkr " tgpfgtkpi 0""

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Kp"vj g"vj guku."y g"dqvj "wg"vj g"J NCRKku'eqnkup" f gvgevkp" cni qtkj o "cpf "qwt" qy p" xqno g"dcugf "eqnkup" f gvgevkp" cni qtkj o 0'J NCRK'ej geni'qpn' "eqnkuppu" dgw ggp" uwthceg"dcugf "i tcr j leu'cpf "j cr vkr "vkr " r qkp'v'f guetkdgf "kp"ej cr vgt"50'Vj ku'eqnkup"ku" tgutlevgf "y kj "c"r qkp'v'eqpve0'Kp"qtf gt"v"j cxg" c"o wnk'eqpvev" hqtg"o qf gn"y g'j cxg" wugf "c"xqz gr'dcugf "tgr tgu'p'cvkpp"qh'f ghqto cdng" f cv' hqt "xqz gr'dcugf "eqnkup"ej geni' f guetkdgf "kp"ej cr vgt"50"

"

"

"

6.2.3 Graphical Renderer

"

C"5F "i tcr j leu"tgpfgt"ku"cp" guugpvkn"kuwg"lp"vj g"j cr vke"tgpfgt"lpi 0'Vj g"j cr vke" cr r nkecvkp"o wuv"j cpfng"j cpf "g{g"eqqtfkpcvqp"ht"tgrkuo "qh"xtwcn"gpvktqpo gpv0' Hqt" i tcr j lecn"tgpfgt"lpi ." Qr gpI N" y j lej " ku" eqo r cvkng" cpf " kpf gr gpfgpv" qh" vj g" qrgtcvki " u{uvgu u" ku" wugf 0' D{ " wukpi " Qr gpI N" qpg" ecp" fgxgr " cr r nkecvkpu" kpf gr gpfgpv"qh"vj g"b qf gn"qh"vj g"i tcr j lecnlectf "cpf "vj g"ctej kgewtg" qh"vj g"r tqeguqt0' K'ku'cnuq'r quukng"vq'tgcej "ugxgcn' gzc o r ngu"cpf "f qewo gpvcvqp"cdqw'Qr gpI N'ukpeg" k'j cu"dgego g"uq"eqo o qp"lp"vj g"hgfr 0'Cpcqvj gt"cf xcpvc i g"ku"vj g"Qr gpJ cr vkeu" vqmk' ku" r cwtpgf " chgt" vj g" Qr gpI N " CRK" o cnkpi " k' hco kkt " vq" i tcr j leu" r tqi tco o gtu"cpf "hckkcvki "kvgi tcvkp"y kj "Qr gpI N"cr r nkecvkpu0'

"

Cnj qwi j "xqzgn'dcugf "o qf gn'wugf "ht"eqmkukp"cpf "f ghqto cvkqp."f wg"vq"tgrcn'vko g" f go cpf u."cpf "cej kxg"eqo r wcvkpcn'ghhkegpe{ "cpf "o qtg"ceewtcvg"xlwcnk cvkqp."c" uwhceg'dcugf "tgpfgt"lpi "o gj qf "ö*Marching Cubes*ö"ku"wugf "vq"gzvtf g"vj g"xqno gtle" o qf gn' f {pco lecn{ "cpf " ghhegpn 0' Vj g"o ctej kpi " ewdgu" cni qtkj o " ku" vj g" o quv" r qr wct"uwhceg"dcugf "cni qtkj o "wukpi "xqzgn'f gpuk{ "xcnvgu'dgecvug"qh"ku"ghhkegpe{ " vq" r tqf weg" c" j ki j " s wcnk{ " xlwcnk cvkqp" qh" vj g" qdlgev' uwhcegu0']65_ " Rngcug" ugg" Cr r gpfkz'E'ht"o ctej kpi "ewdgu"b gj qf 0'

"

Qpg"qh"vj g"qdlgev"ku"gu"qh"vj ku"vj guku"ku"vq"vug"j ki j "ngxgn'f guki p"vqnu"vq"o qf gn'c"xtwcn' gpvktqpo gpw."cpf "j ki j "ngxgn'i tcr j lecn"tgpfgt"lpi "r cenai gu"vq"xlwcnk g"vj g"xtwcn' gpvktqpo gpv0'Vj g'htu'vcuniku"vq"hp" c"i qqf "f cv'htqto cv'ht"tgr tgugpvki "5F"b qf gr0"

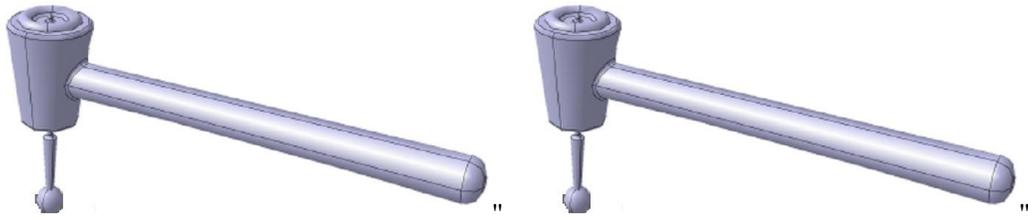
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"

"

"



ECVK'F CVCUGV"

5F "Y CXG'HTQP V'öQDLö'F CVC'UGV"

Hki wtg'80" Eqpuxtukqp"qh'ECVK^{VO}"lpv"Y cxgltqpV'öQDLö'hqto cv"

"

"

Vj g"Y cxgltqpV'öQDLö'hkg'hqto cv'ku'c'Ucpf ctf '5F "qdlgev'hkg'hqto cv'etgcvgf 'hqt'wug"
 y kj " 5F " I tcr j le" r tqi tco u0' Qdlgev' Hkgu" ctg" vgzv' dcugf " hkgu" uwr r qt vpi " dqj "
 r qn(i qpen'cpf "htgg/hqto "i gqo gvt {"*ewtxgu"cpf "uwthegu+0' Cp"QDL'hkg"ku"i qpf "hqt"
 uvtkpi "c" f guetkr vqp"qh'vj g"uwthceg"qh" c"5F "qdlgev."eqo r qugf "qh'vkcpi ngu"qt"j ki j gt"
 f gi tgg'r qn(i qpu0Rgcug'ugg'Cr r gpf kz'D'hqt'y cxg'htqpV'hkg'hqto cv0"

"

Vqqn'O clp'Dqf { "ku'eqptqmgf "d{ "cp" QDL'y j lej "ku o qf grgf "y kj 'ECVK0'Vqqn'J gcf "
 ku'eqptqmgf "d{ "xqzgn'f cv"ugv'cp0'Uq"vj cv'wugt "ecp"ej qqug"f hgtgpv'v r g. "f hgtgpv"
 uk' g'cpf "f hgtgpv'r tqr gt vgu"qh'vqqn'j gcf u0'Ego dlpcvqp"qh'vqqn'o clp"dqf { "cpf "vqqn'
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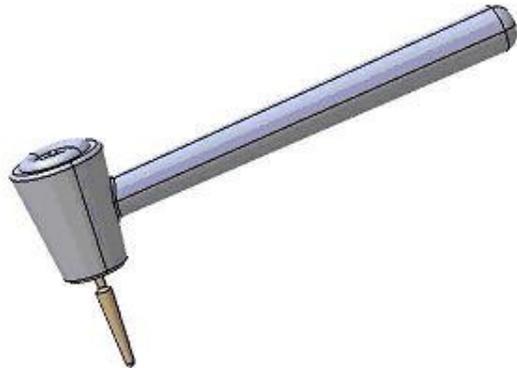
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"



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"

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J gcf "cpf "Dqf { "qh'vj g'Ewvpi "Vqqn'

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"

"

6.2.4 Stereovision and Sound Rendering

"
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Uvgtgqxkukqp'cpf "uqwpf "ghgeu'ctg'ko r ngo gpv'f "vq'vj g'cr r rkecvkqp0Vj g'y qtf "\$uvgtgq\$" "
eqo gu'htqo "vj g'I tggm'y qtf "\$uvgtgqu\$"y j lej "o gcpu" hko "qt'uqrf 0Y kj "uvgtgq'xkukqp"
wugt "ecp'ugg'cp'qdlgev'cu'uqrf "lp'vj tgg'ur cvkcn'f ko gpukqpu*y kf vj . "j gli j v'cpf "f gr vj +0'
K'ku'vj g'cf f gf 'r gtegr vkqp'qh'vj g'f gr vj 'f ko gpukqp'vj cv'o cngu'uvgtgq'xkukqp'uq'lej "cpf "
ur gekr0"

"
Gcej "g{g'ecr wtgu'ku'qy p" xkgy "cpf "vj g'vy q'ugr ctcv'ko ci gu'ctg'ugpv'qp'vq'vj g'dtckp"
hqt'r tqeguakpi 0Y j gp'vj g'vy q" ko ci gu'cttkxg'uko wncpgqwur' "lp'vj g'dcenlqh'vj g'dtckp."
vj g'ctg'wpxgf "lpv'qpg" r lewtg0Vj g'dtckp"eqo dlpgu'vj g'vy q'ko ci gu'd{" "o vej kpi "vr "
vj g'uko krtkkgu"cpf "cf f kpi "lp'vj g"uo cm'f khtgpegu0Vj g"uo cm'f khtgpegu"dgvy ggp"
vj g'vy q'ko ci gu'cf f "vr "vq'c'dki "f khtgpeg'lp'vj g'hpcnr lewtg0Vj g'eqo dlpgf 'ko ci g'ku"
o qtg'vj cp'vj g'lw'o "qh'ku'r ctu0K'ku'c'vj tgg/f ko gpukqpcn'uvgtgq'r lewtg0"

"
Et {ucriG{gu5 "Hki wtg" 806+" ku" wugf " vq" cf qr v' vj g" uvgtgqxkukqp" lpv' vj g" uko wrcv'kqp"
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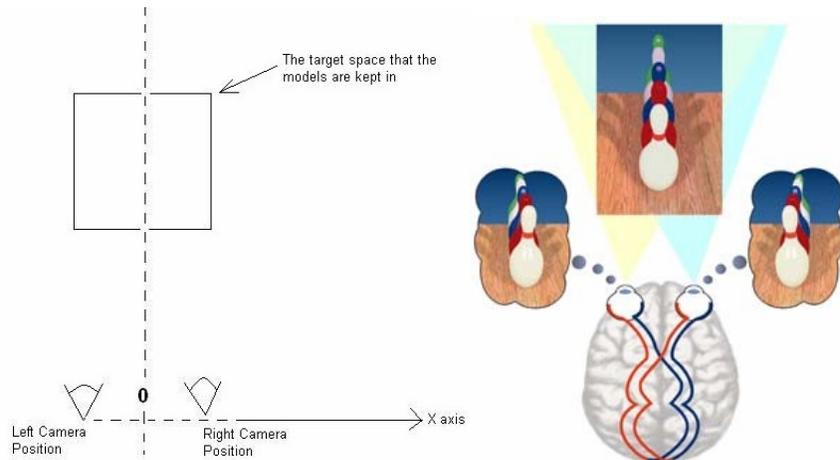
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Vj g" Qr gpI N' hwpvckp" oi rF tcy Dwhhgt* iöcmqy u"vj g" f gxgrqr gt "vq" ur gekh{ "y j lej "dwhhgt" uwdugs wgpv" Qr gpI N' f tcy kpi u" cpf " tgpfgt kpi u" uj qwf " dg" f kgevgf " vq0 Y kj " pqto cni' pqp/ uvgtgq" Qr gpI N' f qwdrg/ dwhhgtkpi . "vj g" f gxgrqr gt "y kn' v{ r lecn{ " f tcy "vq" vj g" \$dcenti' dwhhgt\$ " i rF tcy Dwhhgt* I NaDCEM++ " cpf "vj gp" \$uy cr "dwhhgtu\$ " kp" qtf gt "vq" r w' y j cv' j cf " dggp" f tcy p" vq" vj g" dcenti' dwhhgt" qp vq" vj g" \$htqp v' dwhhgt\$. "y j lej " tgr tguqp v" vj g" xkukdrg" f kur rc { 0 "

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"

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::

Y j gp" f tcy kpi " vj g" nghv" g{ gdu" xkgy " vq" vj g" dcent/nghv" dwhgt. " vj g" eco gtc" r qukkqp" ku" cf lwugf " uq" vj cv" vj g" eco gtc" ku" o qxgf " vqy ctf u' nghv" qp" vj g" Z" czku" d{ " j crh" vj g" co qwpv" qh" vj g" qr gpkpi " dgwy ggp" vj g" wy q" g{ gu" Vj gp" vj g" r gtur gevkg" qh" vj g" xkgy r qkp" v" ku" w" f cvgf " uq" vj cv" vj g" nghv" g{ g" nqmi" cv" vj g" uco g" vcti g" Vq" f q" vj ku. " vj g" tgevcpi wct" dqz. " tgr tgugpvkpi " vj g" rko ku" qh" vj g" ur ceg" vj cv" y kn' dg" tgpf gtgf " qp" vj g" uetggp. " ur gekkfg " d{ " oi rH wuwo ö" hwpevkqp" ku" o qxgf " vqy ctf " tki j v" qp" vj g" Z" czku" d{ " c" ur gekkfg " co qwpv" Vj ku" r tqegu" ku" kmwut cvgf " kp" Hki wtg" 8070Uko kctn" y j gp" vj g" tki j v" g{ gdu" xkgy " ku" f tcy p" vq" vj g" dcent/ tki j v" dwhgt. " vj g" eco gtc" ku" o qxgf " vq" vj g" tki j v" qp" vj g" Z" czku" d{ " j crh" vj g" co qwpv" qh" vj g" qr gpkpi " dgwy ggp" vj g" wy q" g{ gu" cpf " vj g" H wuwo " ku" cf lwugf " O' K' ku" r qukkdrg" vq" eqpv" qn' lvg" t gq" xkukqp" d{ " vj g" cr r rkecvkqp" o gpw0

Vj g" j gctkpi ø' ugpug" qh" j wo cp" dgkpi u" ku" lpf kur gpucdrg" kp" xkt wcn' t gcnk" { " cr r rkecvkqp" o" Kp" cf f kkkqp" vq" vj g" xkwcn' ghgew" cpf " hqteg" hggf dcent/ wf kq" ghgew" ecr cdkk" { " ku" cf cr vgf " vq" vj g" cr r rkecvkqp" d{ " Qr gpI Nøu" hwpevkqp" o" Vj g" uqwpf " ghgew" u' dgeqo g" cevkg" y j gp" c" tqvcvkqp" qh" ewwki " vq" qn' gxgpv" t kugu" O" qtgqxt" c" i tlpf kpi " uqwpf " ghgew" vj j lej " dgeqo gu" cevkg" f wtkpi " vj g" i tlpf kpi " qr gtcvkqp" qh" vj g" f ghqto cdrg" qdlgev" ku" lpgi tcvgf " vq" vj g" u{ ugo " Vj g" uqwpf " uctw" y j gp" vj g" vq" n' vq" wej gu" vj g" f ghqto cdrg" qdlgev" cpf " uqr u" y j gp" vj g" qdlgev" ku" w" pvq" wej gf " O'

6.2.5 Force Rendering

Hqteg" ecrewrvkqp" o qf gn' r r{ u" cp" ko r qtvcpv" tqng" cv" vj g" j cr vke" tgpf gt kpi " u{ ugo " hqt" ewwki " qr gtcvkqp" o' F gr gpf kpi " qp" j qy " vj g" hqteg" ecrewrvkqp" o qf gn' j cu" dggp" ko r ngo gpvgf . hqteg" tgpf gt kpi " o c{ " tgs wkt" g" xgt { " hcu" v' t gur qpug" vko gu" O' K' E j cr vgt " 7. " vj g" hqteg" ecrewrvkqp" o qf gn' ku" f kwugf " hqt" c" " hcu" v' t gur qpug" vko g" O' Vj g" qwr w" hqteg" eqo r qpwp" u' ctg" ewwki " hqteg. " xkdtcvkqp" hqteg" f wg" vq" ewwki . " cpf " i tcvk" { " hqteg" f wg" vq" y gli j v" qh" vj g" vq" n' Vj g" uqwpf " hqtegu" ctg" ko r ngo gpvgf " y kj " J F CRK' Cnuq" qv" gt" hqteg" r ctco vgtu" = ucvke" cpf " f { pco le' htlevkqp" u' ctg" ko r ngo gpvgf " y kj " J NCRK' Vj g" pgv" hqteg" qwr w" ku" uwo o cvkqp" qh" vj g" uqwpf " hqtegu" Vj g" vqts wg" qwr w" ku" i gpgtcvgf " f wg" vq" vj g" qwr w" pgv" hqteg" cpf " ewwki " qr gtcvkqp" tgrcvgf " y kj " tqvcvkqpcn" ur ggf " qh" vj g" ewwgt" O' K' ku" r qukkdrg" vq" gpcdrg" cpf " f kucdrg" vj g" hqteg" cpf " vqts wg" qwr w" u' d{ " öForce & Torque Outputs" r cpn' luj qy p' kp" VCDNG' 8040"

Vj g'xldtcvkqp'hqteg"cpf "i tctxk{ "hqteg"ku"qr vkqpcn'cpf "k'ku'r quukdrg"vq"eqpvtqn'd{ "y g" cr r rncvkqp"o gpw0Vj g'htgs wqpe{ "cpf "co r rkwf g'qh'yj g'xldtcvkqp'hqteg"ecp'dg"eqpvtqn' y kj "yj g'xldtcvkqp"ugwkpi "o gpw0Vj gug'r ctco gvgtu'ctg" rko kqf "kp"qtf gt" vq'r tqvgev'yj g" j cr vef'gxlkg0Vj gug'eqpvtqn'r cpgnu'ctg'uj qy p'lp"VCDNG'8040"

"

Cmj qwi j "yj g"J F CRKj cu"j ki j "htgs wqpe{ "qh'hqteg"tght guj gu"*ç3222"J | +:"yj g"J NCRK j cu'c'hqy gt'htgs wqpe{ "qh'gxgpvj" cpf rkp "ç322"J | +0Vj ku'f khtg gpeg"ecwugu'r tqdrgo u" tgpf gtpi "qwr w'hqtegu0"

"

Kp"qtf gt"vq"j cxg"c"ucdrg"hqteg"tgpf gtpi . "y g"ko r ngo gpv'c"hnkt"y j lej "eqpvtqn'yj g" qwr w'hqtegu0Vj g"o clp"kf gc"qh'yj g"hnkt"ku="kh"wggt"o cnguc"utcki j v'o qvkqp."kp"c" ewwkpi "qr gtcvkqp."k'ku'pqv'r quukdrg"vq"lwo r "yj g'tgukucpeg"hqteg"vq"cpqj gt"ftgekvp" qt'f kuuko kct"o ci pkwf g'lp"gxgt{ "ko g'uvgr 0"

"

"Vj g"cr r rkgf "hnkt"ej gemu'yj g"r tgxkqwu"hqteg"cpf "ewtgpv'hqteg"ecrewcvgf "cpf "kh'yj g" f khtg gpeg"öDelta Forceö"ku"uq"j wi g0Vj g"hnkt"o cnguc"uo qqj kpi "qp"ewtgpv'hqteg" y kj "cfff kpi "cp"öEpsilonö"hqteg" f khtg gpeg"qp"r tgxkqwu"hqteg0Vj ku"gpcdrgu"ucdrgu" hqteg"qwr wu'dqj "lp"o ci pkwf g'cpf "lp"ftgekvp0Vj g'F gnc"Hqteg"cpf "Gr ukqp"ecp'dg" eqpvtqn'lp'yj g"uqhvy ctg0Vj g'f ghcwn'xcnrgu'ctg"ugrgev'f "cu="20P "hqt"fgnc"hqteg"cpf " 027'hqt"gr ukqp'hqteg0""

"

VCDNG'808" Vj g'Hqteg'Hnkt"

```

Ki ( ( F_{PREVIOUS}^{\rightarrow} - F_{CALCULATED}^{\rightarrow} ) > DeltaForce
.....} "
            1*Wf fcvg'Ewtgpv'Hqteg'y kj 'Rtgxkqwu'Hqteg+"
..... F_{CURRENT}^{\rightarrow} = F_{PREVIOUS}^{\rightarrow} + Epsilon "
} "
Gng"
} "
            1*Wf fcvg'Ewtgpv'Hqteg'y kj 'Ecrewcvgf 'Hqteg+"
..... F_{CURRENT}^{\rightarrow} = F_{CALCULATED}^{\rightarrow} "
"
i "
Gpf "Ki"
"

```

"

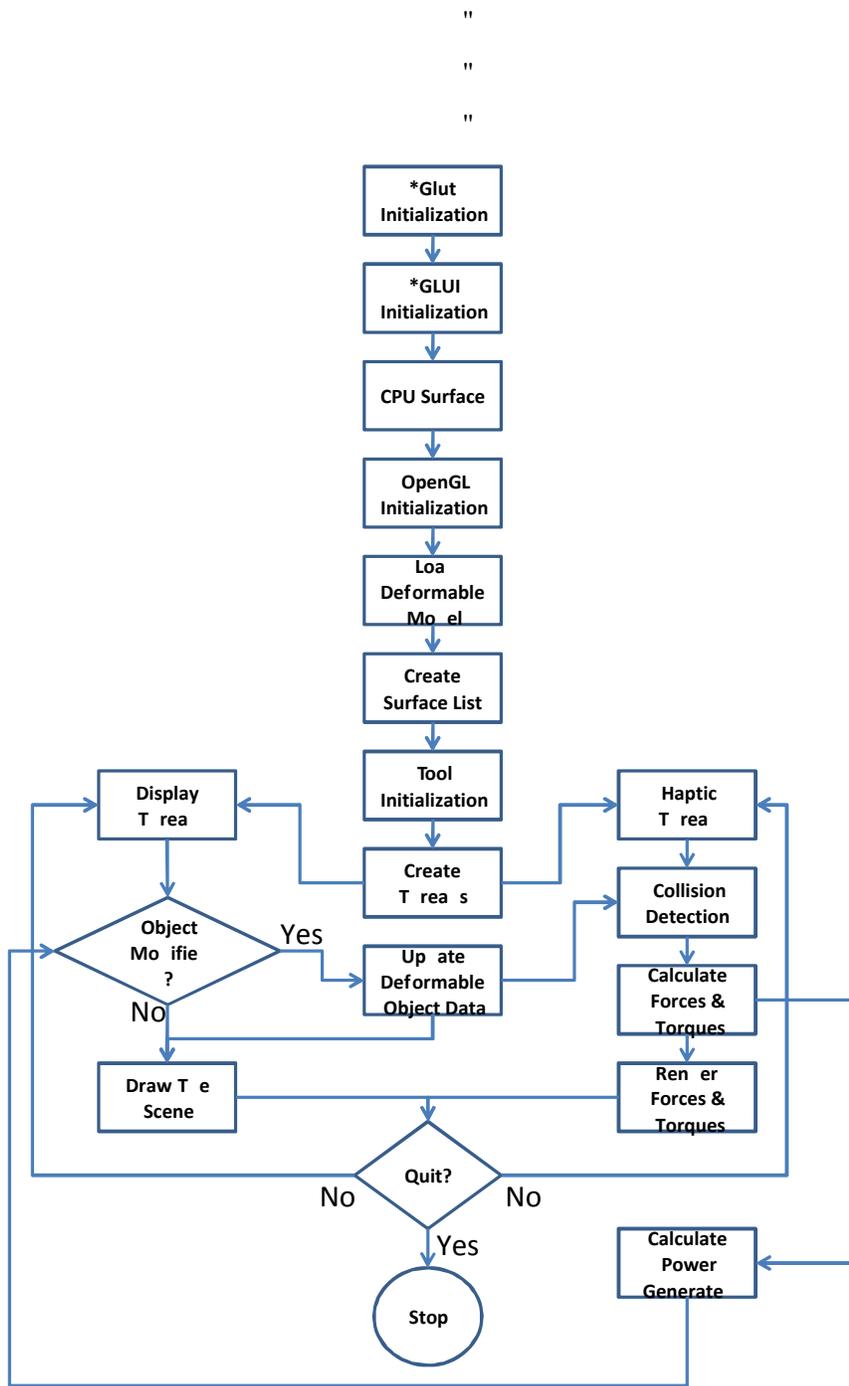
6.3. STRUCTURE OF SOFTWARE

"
Uqhy ctg" ctej kgewtg" ku" kp" o wnk" ó" vj tgcflpi " utwewtg" y j gtg" vj g" j cr vle" cpf " vj g"
i tcr j le" mqr u" uj ctg" vj g" uco g" f cvdcug' Vj gtghqtg. " vj g" u{ pej tqpk cvkp" qh" vj g" y q"
vj tgcflpi" ceeguupi " ku" vj g" o qu'etwelcn'cunlvq' r gthqto 'OUkpeg" dqvj " vj tgcflpi" ctg" vj g"
uco g" f cvdcug. " vj g" utwewtg" t wpu" qp" c" ukpi rg" o cej kpg' O

"
Cv" vj g" uctv" qh" vj g" cr r rlecckp. " vj g" ucpf ctf " lpkckrk cvkpu" hqt " vj g" I NWW" cpf " I NWK
rdtctkgu" *I NWW/ dcugf " E- - " wugt" kpvthceg" rdtct { " y j lej " r tqxkf gu" eqptqni" uwej " cu"
dwwqpu. " ej genldzgu. " tcf kq" dwwqpu. " cpf " ur kpgtu" vq" Qr gpI N" cr r rlecckpu" ctg" f qpg' O
Vj g" r tqi tco " ku" lpkckrk kpi " vj g" Qr gpI N" ugwkpi u" cpf " hqf kpi " qh" vj g" f ghqto cdrg" qdlgev"
f cv" f gr gpf kpi " qp" vj g" ugrgevgf " f cv" ug' O' Vj g" utwecg" hku" qh" vj g" f ghqto cdrg" qdlgev" f cv"
kp" 5F " xqzgn'cttc { " ku" etgcvgf ' O' Vj g" o qf gnhqt " vj g" ewwkpi " vqni" ku" hqf gf " cpf " r c tco gvgtu"
hqt " k' ctg" lpkckrk gf " dghqtg" vj g" f kur r { " cpf " j cr vle" vj tgcflpi" uctv" y qtnkpi ' O

"
Chgt" vj g" lpkckrk cvkpu. " vj g" f kur r { " cpf " j cr vle" vj tgcflpi" uctg" etgcvgf " vq" y qtn' O' Vj g" ug"
vj tgcflpi" qtm' eqpvkpwqwu" { " vpvk' vgt o kpcvkp" qh" vj g" cr r rlecckp' O' Vj g" hgs wge { " qh" vj g"
j cr vle" vj tgcflpi" j cu" vq" dg" cv' rgeuv' 3222J | " vq" tgpf gt' eqpvkpwqwu" cpf " ucdkrg" hqtegu" hqt " vj g"
j cr vle" f gxleg' O' K' ku" ko r quukrg" vq" tgej " vj cv' hgs wge { " hqt" vj g" i tcr j lecn' vj tgcflpi"
dgecwug" qh" vj g" eqo r rnz " utwewtg" u' t gpf gtgf " qp" vj g" uetggp' O' Hico g " tcvg" ku" vppgeguuct { "
ukpeg" j wo cp" g { " g" ecppqv' f kpi vkuj " vj g" f khtgpeg" dgw ggp" vj g" tghgtuj " tcvgu" i tgcvgt"
vj cp" 52' J | O"

"
Cv" vj g" dgi kppkpi " qh" vj g" f kur r { " vj tgcflpi. " vj g" f cvc" ku" wr f cvgf " kp" ecug" qh" o qf klecckp' O'
Vj g" o qf klecckp" qh" vj g" f cvc" ku" c" eqo r rnz " qr gtcvkp" y j lej " pggf u" c" eqo r wcvkpcrn'
y qtmqcf ' O' Vj gtghqtg" k' ku" pqv' r quukrg" vq" ko r ngo gpv' o qf klecckp" kp" j cr vle" vj tgcflpi"
y j lej " j cu" vq" tgej " c" hgs wge { " i tgcvgt" vj cp" 3222J | " vq" r tqxkf g" ucdkrg" cpf "
eqpvkpwqwu" hqtegu' O' Eqnkukp" f gvgevkp" uj qwf " dg" f qpg" kp" f kur r { " vj tgcflpi" vq" f gekf g"
y j gvj gt" vj g" f cvc" y kn' dg" o qf kkgf " qt" pq' O' Vj g" eqnkukp" f gvgevkp" ecp" dg" f qpg" d { "
wukpi " vj g" J NCRK" ku" hwpvkp" vj cv' ecp" y qtm' kp" enkgpv' vj tgcflpi" y kj qw" cp" kpeqpukvge { "
y kj " vj g" j cr vle" vj tgcflpi" O' kp" ecug" qh" c" o qf klecckp" vj g" f ghqto cdrg" qdlgev" f cvc" y j lej " ku"
wugf " d { " dqvj " vj g" f kur r { " cpf " j cr vle" vj tgcflpi" y kn' dg" wr f cvgf ' O' Vj gtghqtg" vj ku" wr f cvg"
qr gtcvkp" j cu" vq" dg" vj tgcflpi / uchg' kp" qtf gt " vq" cej kxg' hqteg' hggf dcentleqpukvgepv' y kj " vj g"



Hli wtg'808" Vj g'lnqy ej ctv'qh'vj g"Crr rkecvkp"
 Vj g'lvgr u'y kj "ø'tg'vj g'lvcp ftf 'lpk'ek' ek'qpu'qh'vj g'hdtctkgu0

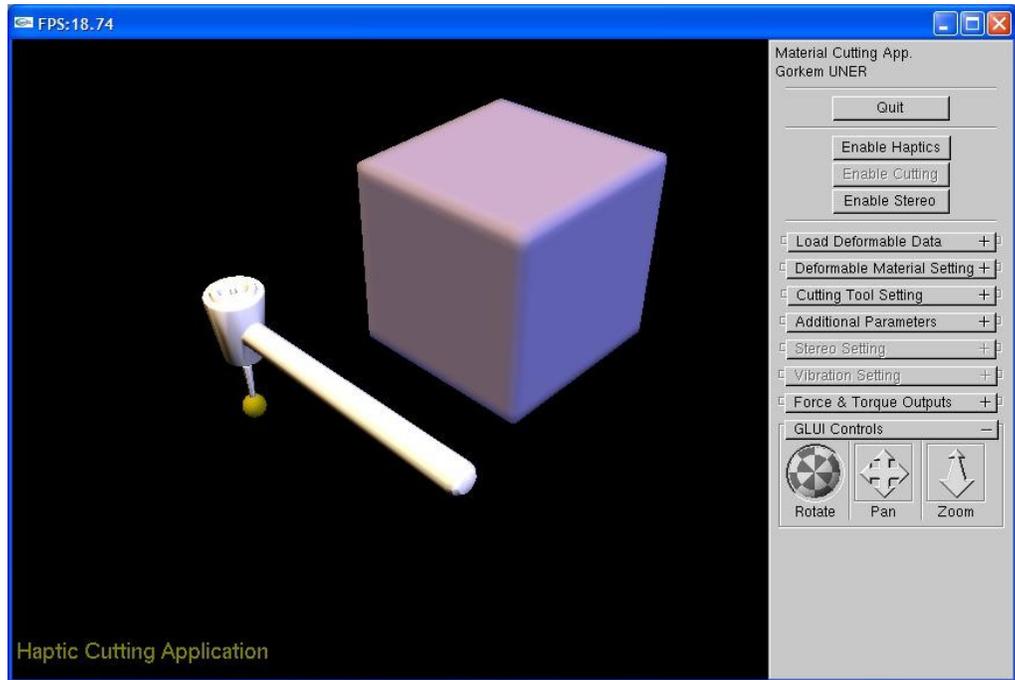
6.4. THE USER INTERFACE

"

ƒp"vj g'wugt'kpvgthceg."vj g'5F"xktwcn!gp xktqpo gpv!penwf kpi "vj g'f ghqto cdrġ"o qf gr!cpf " ewwkpi "vqqr!ctg"tgpf gtgf "y kj "cp"cr r rġcvkqp"eqpvtqr!o gpw'qp"vj g"tki j v'ukf g"qh"vj g" uetggp0"

"

"



Haptic Cutting Application

Hki wtg'80" J cr vġ'Ewwkpi "Cr r rġcvkqp"

"

"

Vj g"o gpw'ecp"dg" wugf "v"cf lwuv"vj g"r tqr gt vġu"qh"f ghqto cdrġ"qdlgev."ej cpi g"vj g" ewwkpi "vqqr!i gqo gvt {. "ukf g."cpf "tqvcv kqp"ur ggf ."cev!xcv kpi "qt"fgcev!xcv kpi "vj g"j cr vġ" f gxleg0"

"

ƒp"vj g'v!krġ"dct"vj g"i tcr j kecn'tgh!gij "tcvġ"ecp"cnq"dg"qdugtxgf 0'Uqo g"uetggpuj qw"qh" vj g'wugt'kpvgthceg"ftkpi "ecp"dg'x!ky gf "kp"vj g'hki wtgu'cv"vj g'gpf "qh"vj k!ej cr vġt0"

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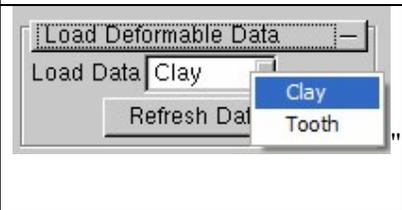
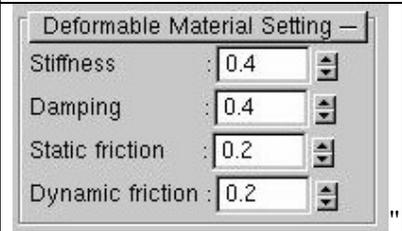
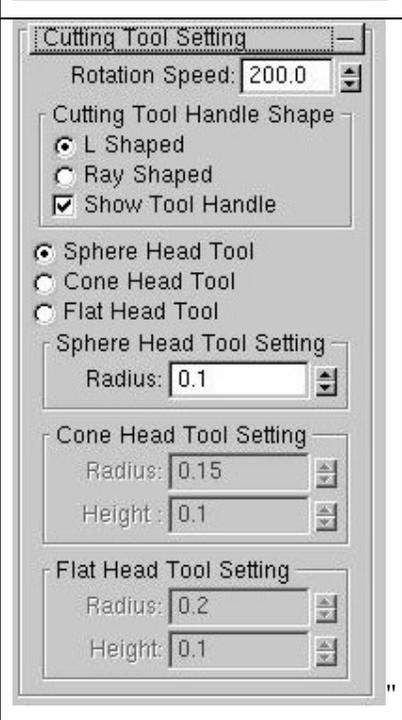
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VCDNG'804'J cr vE'ewwłpi 'Crr rłecvłqp'O gpw

	<p>Crr rłecvłqp"Eqpvtqr'Dwwłqp'ctg"wgf "hqt'emłkpi " vj g"cr rłecvłqp."gpcdrłpi "qt"f kucdrłpi "vj g"j cr vE" f gxleg."vj g'ewwłpi "cpf "vj g"łvgtgq'xłkłqp0'</p>
	<p>Nqcf " F ghqto cdrę" F cvc" Rcpgrł' kpenwf gu" vy q" f kłhgtgpv" f cvc" ugw" hqt" f ghqto cdrę" qdlgev" erc{" ewdg" cpf " vqvy 0' dTghgıj " F cvcö" dwwłqp" ku" hqt" rıcf kpi "f cvc"ugw"chıgt"ugrgevłqp0'"</p>
	<p>F ghqto cdrę"O cvgtkcn' Ugwłpi "Rcpgrł' kpenwf gu" vj g" r j { ułecn'r tqr gt vłgu"qh'ugrgevıf "f ghqto cdrę"qdlgev." uvej "cu="Ułłhpıuu." F co r kpi ."UcvE"Hłevłqp" cpf " F { pco le"Hłevłqp0'</p>
	<p>Ewwłpi "Vqqrł'Ugwłpi "Rcpgrł'kpenwf gu"vj g"r tqr gt vłgu" qh" ewwłpi " vqqrł' Tqcvłqp" ur ggf " qh" vj g" ewwłpi " j gcf ." ewwłpi " vqqrł' j cpf rę" uj cr g" *dNö" qt" Tc{ " uj cr gf +"cpf "r j { ułecn'r ctco gvgtu"qh'ugrgevıf "vqqrł' j gcf "i gqo gvłgu"ctg" vj g"r ctco gvgtu" hqt" ewwłpi " vqqrł'Uj qy "vqqrł'j cpf rę"ej genłqz "ku" hqt "gpcdrę"qt" f kucdrę"vqqrł'j cpf rę"i gqo gv { 0'</p>

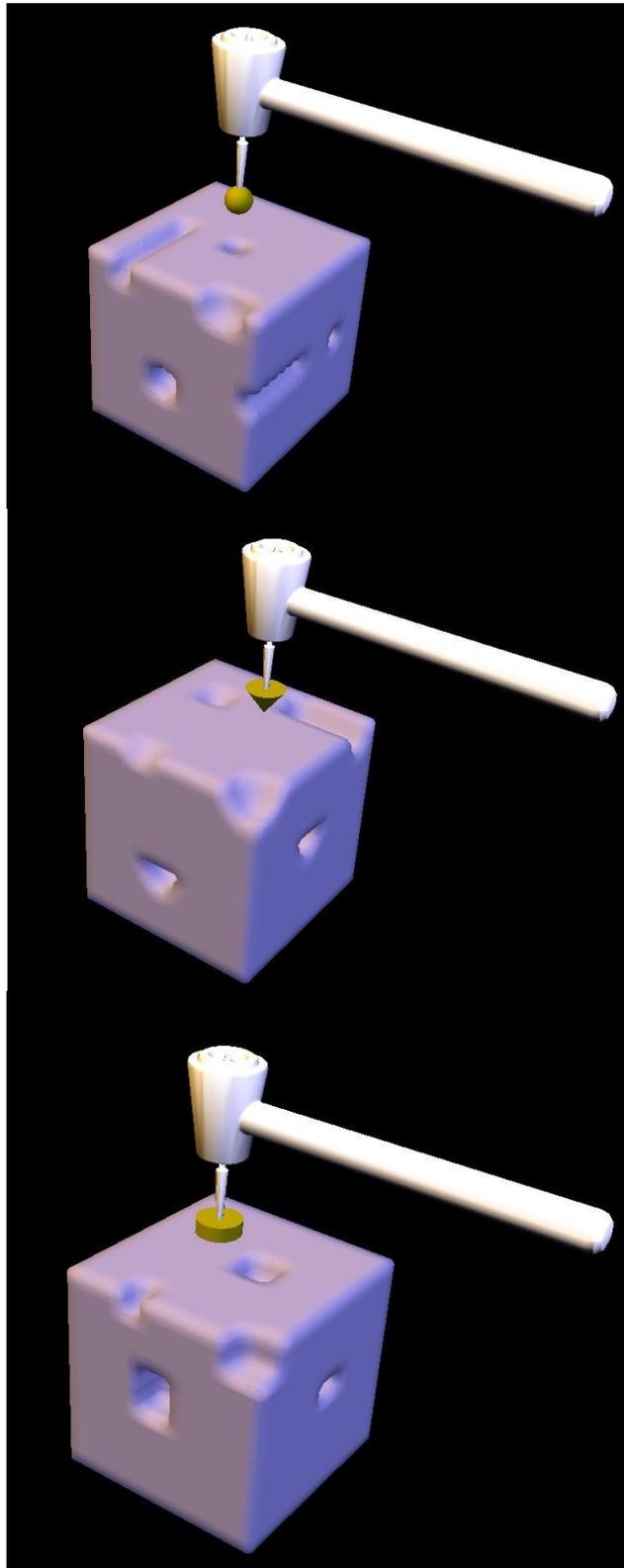
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VCDNG'80#J cr vle'Ewłpi "Cr r rłecvłp'O gpw*Eqv0"

<p>Additional Parameters</p> <ul style="list-style-type: none"> <input type="checkbox"/> Enable Vibration <input type="checkbox"/> Enable Sound <input checked="" type="checkbox"/> Enable HL <input type="checkbox"/> Enable Gravity <input type="checkbox"/> Show Results <input checked="" type="checkbox"/> Enable Filter 	<p>Cf f kłkpcn' Rctco gvgt" Rcpgn' kpcnł gu" uqo g" cf f kłkpcn' rctco gvgtu" hqt" ewłpi " o cvgtkcn" cr r rłecvłp0' K' ku" r quukdng" vq" gpcdng" xkdtcvłp." uqwpf "cpf "i tcvkł{ "ghgcu" hqt "kpetgculpi "tgerkł "qh" vj g" cr r rłecvłp0' 0Uj qy " tguvnu0" ej gendqz "ku" hqt" r tlpvłpi " ewłpi " tguvnu" kp" tgen' vko g0' 0Gpcdng" hngt0" ej gendqz "ku" hqt " gpcdrłpi "cpf "f kucdrłpi "vj g" hqt eg' hngt0"</p>
<p>Stereo Setting</p> <p>Eye Adjsut : -0.002</p> <p>Eye Offset : 0.08</p>	<p>Uvgtgq" Xkukqp" Ugwłpi " Rcpgn' kpcnł gu" vj g" rctco gvgtu" wugf " hqt" uvgtgq" xkukqp0' Vj ku" r cpgn' ku" cevłxg" y j gp" 0Gpcdng" Uvgtgq0" dwwqp" ku" wugf 0'</p>
<p>Vibration Setting</p> <p>Vib. Frequency : 100.0</p> <p>Vib. Amplitude : 0.03</p>	<p>Xkdtcvłp" Ugwłpi " Rcpgn' kpcnł gu" vj g" rctco gvgtu" wugf " hqt" xkdtcvłp0' Vj ku" r cpgn' ku" cevłxg" y j gp" 0Gpcdng" Xkdtcvłp0" ej gendqz "ku" gpcdngf 0'</p>
<p>Force & Torque Outputs</p> <ul style="list-style-type: none"> <input checked="" type="checkbox"/> Force in X Direction <input checked="" type="checkbox"/> Force in Y Direction <input checked="" type="checkbox"/> Force in Z Direction <input checked="" type="checkbox"/> Torque in Raw <input checked="" type="checkbox"/> Torque in Pitch <input checked="" type="checkbox"/> Torque in Roll 	<p>Hqt eg" ("Vqts wg" Qwr wu" Ugwłpi " Rcpgn' kpcnł gu" ej gendqz gu" hqt " gpcdrłpi "cpf "f kucdrłpi "vj g" j cr vle" qwr wu" hqt egu" cpf "vqts wgu" kp" cnłf kt gevłqpu0'</p>
<p>GLUI Controls</p> <p>Rotate</p> <p>Pan</p> <p>Zoom</p>	<p>I NWK Eqpv tqm" Rcpgn' kpcnł gu" 0T qvcv0. " 0Rcp0" cpf "0\ qqo 0" ur gekn' dwwqpu" hqt " eqpv tqmłpi " vj g" 5F "i tcr j kcnłkpvgthceg" gcukł 0'</p>

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 "
 "



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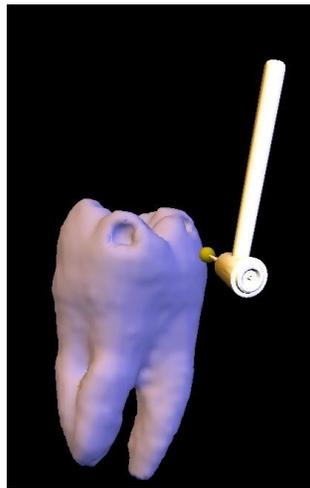
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6.5. CASE STUDY

C"ecug"uwf { "hqt"tgr tgugpvkpi "vj g"fgpvcn"ewwvki "y qwf "dg"vj g"dguv"y c { "vq"ej gen"vj g" tgcruo "qh"ewwvki "hqt"eg"o qf gn"cpf "cr r rkecvkp"tgcrkuo 0 Kp"j cr vke"ewwvki "cr r rkecvkp." c"vqvj "f cve"ku"ko r ngo gpvfg "cu"kmwutcvfg "kp"Hki wtg"8 B20Vj g"xt wcn'gpvktqpo gpv"kp" vj g"j cr vke"kpvgthceg"ku"vj g"r rceg"y j gtg"vj g"tghetgpeg"eqpvtn"kp"r w"ku"i gpgtcvfg 0Vj g" ewwvki "hqt"eg"cpf "vqts wg"ku"ecr ewrcvfg "ceeqt f kpi "vq"qwt "ewwvki "hqt"eg"cpf "vqts wg"o qf gn" f guetkdgf " kp" ej cr vgt" 7" y kj " vqvj au" o cvgtken" r tqr gtvku=" uvej " cu" ukhpguu" cpf " f co r kpi 0"

"



Hki wtg"8Q " F gpcn"Ecug"Uwf { "Uetggpuj qv"

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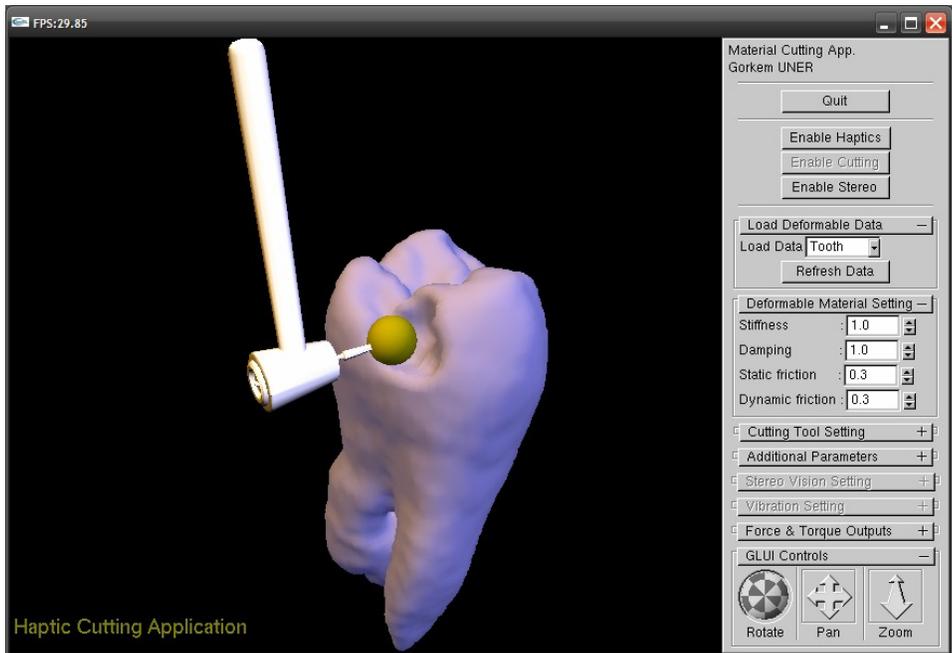
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CHAPTER 7

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DISCUSSION & CONCLUSION"

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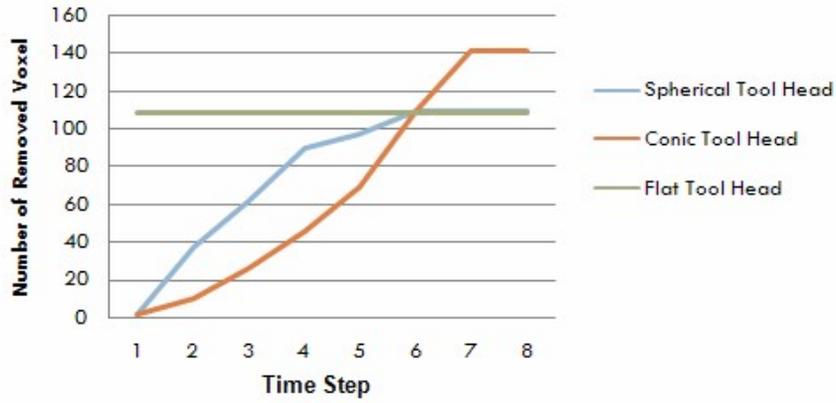
7.1. CASE STUDY AND RESULTS

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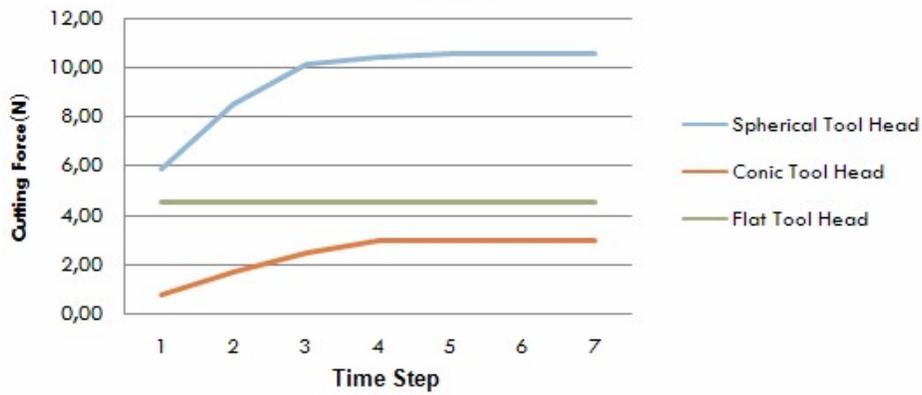
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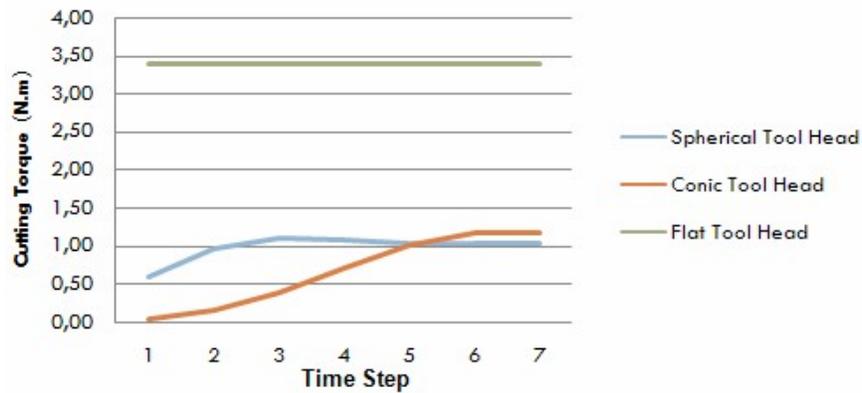
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Cutting Force



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Cutting Torque



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7.3. BENEFITS

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7.4. PROBLEMS

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7.5. FURTHER DEVELOPMENT

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7.6. SUMMARY

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REFERENCES

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-]37_ Eck"\ 0"F km"l0"Rc{ cpf gj ."U0"*Toward Deformation Modeling with Haptic Feedback.*" Rtqeggf kpi u" qh' 4222" CUO G" U{o r qukwo " qp" J cr ve"Kpvt hceg" hqt" Xktwcn" Gpxktqpo gpv" cpf " Vgrg/Qr gtcvkqp." 4222"
- "
- "
- "
-]38_ EJ CK5F ."CHAI 3, [j wr <ly y y Qej ck5f Qti J](#) ."Cwi wuv'35.'4229"
- "
-]39_ Ej guj ktg."F0 0" Gxcpu." O0C0" F gcp." F00"*Haptic Modeling – An Alternative Industrial Design Metrology.*"GwtqJ cr vku"4223."4223"
- "
- "
-]3: _ Eqj gp."C0" Ej cp."G0"*Six Degree-of-freedom Haptic System as a Desktop Virtual Prototyping Interface.*"UgpcDng"Vgej pqmji kgu."Kpe0" 3; ; ; "
- "
- "
-]3: _ Ej gp." J 0E0" J gpi ." R0C0" Uwp." J 0" *Direct Haptic rendering of Isosurface by Intermediate Representation,*"XTUV022."4222"
- "
- "
-]42_ Fgrkpi gwg" J 0" Eqvp" U0" C{cej g" P0" *A Hybrid Elastic Model Allowing Real-Time Cutting, Deformations and Force -Feedback for Surgery Training and Simulation.*" Eqo r wgt" Cplk cvkqp." 3; ; ; 0 Rci gu<92/: 3"" Rtqeggf kpi u."48/4; "O c{ "3; ; ; ""
- "
- "
-]43_ Gtkmuaqp."O0 0"*Haptic and Visual Simulation of a Material Cutting Process.*"MVJ "Vgej pqmji { "cpf "J gcmj ."4225"
- "
- "
-]44_ Hkuj gt."C0"Xcpeg."l00 0"*PHANTOM Haptic Device Implemented in a Projection Screen Virtual Environments.*"RVIGI XG"4225"
- "
- "
-]45_ I gqti {." C0" Nlp." O0E0" I qwuej ctm" U0" Vc{mjt."T0" *H-Collide: A Framework for Fast and Accurate Collision detection for Haptic Interaction.*"Rtqe0KGG"Xktwcn" Tgcrkv{ "Eqphgtgpeg."3; ; ; "
- "
- "
-]46_ I kpplpk" O0" Uqctgu." E00" Ectxcnj q." T00 0" *Ultimate Tensile Strength of Tooth Structures.*"Gngxkgt"Nf 04226"
- "
- "

-]47_ I kduqp." UHHO" O kvej ."D0" C" *Survey of Deformable Modeling in Computer Graphics.*"VT/; 9/3; .P qxgo dgt"3; ; 9"
- "
-]48_ I kduqp." UHHO" O kvej ." D0" *Beyond Volume Rendering: Visualization, Haptic Exploration, and Physical Modeling of Voxel-based Objects.*" O kuwdkuj k'Ggevtke" Tgugctej "Ncdqtcvqtkgu." "Lcpwct { " 3; ; 7"
- "
-]49_ I qwæj cm"UO" Nkp." O Æ0" O cpqej c." F 0" QDDVtgg-*A Hierarchical Structure for Rapid Interference Detection.*" Rtqeggf kpi u" qh" CEO " Uki i trj ø 8." r r Ø93/3: 2." 3; ; 8"
- "
-]4: _ I wcp{ cpi "Nkw" [wt w\ j cpi ." F 0Y cpi ." L0J cq." Rnw" [0Y cpi ." *Cutting Force Model of Dental Training System.*" Vj g" P cvkqpcn' Uelgpeg" Hqwpf cvkq" qh' Ej kpc." 4225"
- "
-]4: _ Hqung{ ." O 0" Nkp." O Æ0" O cpqej c." F 0" *Efficient Computation of A Simplified Medial Axis.*" UO ø25." Lwpg" 4225"
- "
-]52_ J 5F." *H3D.org Open Source Haptics.*" [j wr <ly y y G 5f Qti I.](#)" C wi wuv" 35." 4229"
- "
-]53_ J q." E0 0" Dcuf qi cp." E0" cpf " Utkpkxcucp." O 0C0" *Ray-Based Haptic Rendering: Force and Torque Interactions between a Line-Probe and 3D Objects in Virtual Environments.*" Vj g" k'pvgtpcvkqpcn" Lqwtpcn' qh' Tqdqvku" Tgugctej ." r r 088: /8: 5." Xqr03; ." Kuwg" 9." Lwn" 4222"
- "
-]54_ J q." E0 0" Dcuf qi cp." E0" cpf " Utkpkxcucp." O 0C0" *Efficient Point-Based Rendering Techniques for Haptic Display of Virtual Objects.*" O cucej wugwu" k'pukwng" qh' Vgej pqrqi { ." r r 088: /8: 5." Xqr0: ." P q07." " Qevqdtg" 3; ; ; "
- "
-]55_ J g." ZI0" Ej gp." [J 0" *Bone Drilling Simulation Based on Six degree-of-freedom Haptic Rendering.*" GWTQJ CRVKEU" 4228." 4228"
- "
-]56_ J uw." Y 00" J wi j gu." LHO" Mcwbo cp" J 0" *Direct Manipulation of Free – Form Deformations.*" Eqo r wgt" I trj leu" *Rtqeggf kpi u" qh" vj g" UK I TCRJ +." Xqr048." P q04." r r 0399/3: 603; ; 4"
- "
-]57_ J wddctf." RO0" *Interactive collision detection.*" k' Rtqeggf kpi u" qh' KGG" U{ o r qukw "qp" Tgugctej " Htqpvgtu" k' Xkt wcn" Tgcirkv." Qevqdtg" 3; ; 5"
- "
-]58_ Ici pqy ." T0" F qtug{ ." L0" *Virtual Sculpting with Haptic Displacement Maps.*" I trj le' k'pvgthceg." r ci g" 347/354." 4224"
- "
-]59_ Iqj puqp." MN0' *Contact Mechanics.*" Eco dtkf i g" Wpkxgtuks{ " Rtguu." 3; ; 9"
- "

-]5: _ Ikp."Y 0" Nko ."[0" Zlg."I 0" Vglkpf gt."Z 0" Ukpj j ."R0" Uwxtcpw."F 0G0"
 " Rtqeggf kpi u"qh"O gf lekpg'O ggw"Xkt wcnT gcrk\{ 'Eqphgtgpeg"4227"
 "
-]5: _ Mkpauj k"U0"Uwi kucnk"[0"Mcpcq."J 0"Hwukicy c."O 0"Cpf "O kvtc."M0V0"
 " *Development of a geometric modeling device with haptic rendering.*"
 " Eqo r wgt"Ckf gf "F guki p"("Cr r rkecvkqp."Xqr0'4"P q0'3/6."4227."Rci gu"
 " 4: 5"/'4; 2"
 "
-]62_ Mko ."N0" M{ tknqw."C0" Uwnj cwo g.I U0" F gudtwp." O 0" *An Implicit-*
 " *Based Haptic Rendering Technique.*" Rtqeggf kpi u"qh" y j g" KGGGITUL"
 " Kpvtgpcvkqpcn" Eqphgtgpeg"qp" Kpvgnki gpvTqdqvu."4224"
 "
-]62c_ Mq±cm" W0" " *Development of Dental Educational Simulation with*
 " *Haptic Device, Vj guku" hqt" y j g" f gi tgg" qh" O cuvgt" qh" Uelgpeg."O GVW."*
 " Ugr vgo dgt"4229"
 "
-]63_ Mwpej gpdgengt."M0L0" Rtqxcpej gt."Y 0F0" *Haptic Display of Contact*
 " *Location.*" 34^j " Kpvtgpcvkqpcn" U{ o r qukwo " qp" J cr vke" Kpvgthcegu" hqt"
 " Xkt wcnGp xktqpo gpv'cpf "Vgrqr gtcvqt" U{ uvgo u" *J CRVKEU026"4226"
 "
-]64_ Nc{eqem" UF0" F c{." C000" *The Haptic Rendering of Polygonal*
 " *Models involving Deformable Tools.*" GwtqJ cr vkeu"4225."4225"
 "
-]65_ Ngg."J 0"Ngg."I0"[cpi ."J U0" *Real-time LOD: Marching-cube-and-*
 " *octree-based 3D Object Level-of-detail Modeling.*" Mqtgc" Uelgpeg"
 " cpf "Gpi kpggtkpi "Hqwpf cvkqp."4224"
 "
-]66_ Nkp." O 0" Ucrkudwt{." M0" *Haptic Rendering – Beyond Visual*
 " *Computing.*" KGGG."4226"
 "
-]67_ Nwpl kp."M0"[ppgto cp."C0"I wf o wpl uuqp."D0" *Proxy – based Haptic*
 " *Feedback from Volumetric Density Data.*" GwtqJ cr vkeu"4224."4224"
 "
-]68_ Ngunqxum{ ."R0"J ctf gtu."O 0"Uj gngn{ ."I 0"Vcnrk"P 0"Lqrk"R0" Mj gf f ct."
 " C0"Gugp."J 0"Dwu."O 0"Tquuk"F 0"Dleej k"C0" *Report on Soft Tissue*
 " *Interaction Demonstrators.*" Vqwej /J cr U{ u"4223."4223"
 "
-]69_ O cj xcuj ." O 0" J c{y ctf ." X0" *Haptic Rendering of Cutting: A*
 " *Fracture Mechanics Approach.*" J cr vkeu/g."Xqr0."P q05."43/P qx/4223"
 "
-]6: _ O cj xcuj ." O 0" J c{y ctf ." X0" *A Fracture Mechanics Approach to*
 " *Haptic Synthesis of Tissue Cutting with Scissors.*" Vj g"Lqj p"J qr nkpu"
 " Wplxgtuks{ ." 4224"
 "
-]6: _ O cj xcuj ."O 0"J c{y ctf ."X0" *Haptic Simulation of a Tool in Contact*
 " *with a Nonlinear Deformable Body.*" Kpvtgpcvkqpcn"U{ o r qukwo " qp"
 " Uwti gt{ " Uko wrcvkqp" cpf " Uqlh" Vkuuwg" O qf grkpi " Ngewtg" P qvgu" kp"
 " Eqo r wgt"Uelgpeg0Rr 0533/542."4225"

"

-]72_ O c j x c u j . " O 0 " J c { y c t f . " X 0 " *High-Fidelity Haptic Synthesis of Contact with Deformable Bodies.* " K G G G " E q o r w g t " U q e l g v { . " C r t k r l ' 4 2 2 6 " " " "
-]73_ O c j x c u j . " O 0 " J c { y c t f . " X 0 " N n q { f . " I 0 " *Haptic Rendering of Tool Contact.* " G w t q j c r v k e u " 4 2 2 4 " R c i g u " 3 2 2 / 3 3 7 " " " "
-]74_ O c u u l g . " V 0 0 " U c r k u d w t { . " I M 0 " *The PHANTOM Haptic Interface: A Device for Probing Virtual Objects.* " C U O G " Y k p v g t " C p p w c n l ' O g g w k p i . " F U E / X q r 0 7 / 3 . " C U O G . " P g y [l q t m ' r r 0 4 ; 7 / 5 2 3 . " 3 ; ; 6 " " " "
-]75_ O c u u l g . " V 0 " *A Tangible Goal for 3D Modeling.* " K G G G . " O c { ' 3 ; ; ; " " " "
-]76_ O e P g g n { . " Y 0 ' C 0 " R w g t d c w i j . " M 0 ' F 0 " V t q { . " I 0 ' I 0 " *Six Degree-of-Freedom Haptic Rendering Using Voxel Sampling.* " U K I T C R J " ; ; ; 3 ; ; ; " " " "
-]77_ O e P g g n { . " Y 0 ' C 0 " R w g t d c w i j . " M 0 ' F 0 " V t q { . " I 0 ' I 0 " *Voxel-Based 6-DOF Haptic Rendering Improvements.* " X q r 0 5 . " P q 0 9 . " J c r v k e u / g . " l c p 0 4 2 2 8 " " " "
-]78_ O k k c t { " c p f " C g t q u r c e g " G r g e v t q p k e u . " *Military and Aerospace j w r < l o c g t g p p p g v e q o l c t v e r g u l c t v e r g a f k u r r c { t e h o A U g e v k q p ? C T E J K (E ? P g y u (C T V K E N G a K ? 8 8 ; 3 6 (M G J Y Q T F U ? ' 4 4 u l o w r c v k q p ' 4 2 c p f ' 4 2 o q f g r k p i ' 4 4 (r ? 5 4 . " C w i w u v ' 4 : . " 4 2 2 9 " " " " " " "*
-]79_ P c x c n l ' C g t q u r c e g " O g f l e c n l ' T g u g c t e j " N e d q t c v q t { . " *Tactile Situation Awareness System.* " " [j w r < l y y y t p c o t r f p c x { t k n c e e g n l w u l ' . " " C w i w u v ' 4 5 . " 4 2 2 9 " " " " " " "](#)
-]7: _ P Q X K P V . " *NOVINT.* " [j w r < l j q o g t p x k p v e q o l i c o g u l i c o g u t j r . " " C w i w u v ' 4 5 . " 4 2 2 9 " " " " " " "](#)
-]7: _ P Q X K P V . " *Virtual reality dental training system.* " [j w r < l y y y t p x k p v e q o I X T F V U J w . " " L w n l ' 3 4 . " 4 2 2 9 " " " " " " "](#)
-]82_ Q n w o w t c " C 0 0 " Y g d u v g t " T 0 0 " K K ' P q r k p " I 0 0 " L q j p u q p " M 0 Y 0 " L c h t { " J 0 " *The Haptic Scissors: Cutting in Virtual Environments.* " T q d q v k e u " c p f " C w q o c v k q p . " 4 2 2 5 . " R t q e g g f k p i u 0 ' K E T C 2 5 0 ' K G G G " k p v g t p c v k p c n l " E q p h g t g p e g " q p . " X q n w o g < 3 . " 3 6 / 3 ; " U g r v 0 4 2 2 5 " " " " " " "
-]83_ Q r g p I N . " *The Industry's Foundation for High Performance Graphics.* " T g t l g x g f " C w i w u v ' 4 5 . " 4 2 2 9 " I t q o " [y y y Q r g p i r 0 q t i " " " " " " "](#)
-]84_ R g t t { . " T 0 0 " H k u n g p . " U H 0 " *Kizamu: A System for Sculpting Digital Characters.* " U K I T C R J " 4 2 2 3 . " r c i g ' 6 9 / 7 8 . " 4 2 2 3 " " " " " " "

-]85_ Rgvgtukpm"C0"Rhguugt."D0"Vlkgf g."W0"J ¾dpg."M0 0"*Haptic Rendering of Volumetric Anatomic Models at Sub-Voxel Resolution.*" GwtqJ cr vku"4223." 4223"
 "
-]86_ Rgvgtukpm"C0"Rhguugt."D0"Vlkgf g."W0"J ¾dpg."M0 0"*Realistic Haptic Volume Interaction For Petrous Bone Surgery Simulation,*" ECTU 4224." 4224"
 "
-]87_ Tcpxc."L0"HD" Cxkrgu."Y 0' C0"*The Virtual Reality Dental Training System -Simulating Dental Procedures for the Purpose of training Dental Students using Haptics.*"Rtqeggf kpi u'qh'yj g" Hqwtvj " RJ CP VQO "Wugtu" I tqwr "Y qtmuj qr .P qxgo dgt"3; ; ;"
 "
-]88_ Twur kpk" F(EO" Mqrctqx." M0" Mj cvkd." Q0"*The Haptic Display of Complex Graphical Environments.*" Kp" Ego r wgt" I tcr j kcu" Rtqeggf kpi u." UK I TCRJ ."NquCpi grgu."Ecrkqtplc."Cwi wuv"3; ; 9"
 "
-]89_ Uerkuwt{."LMO"Vctt."E0"*Haptic Rendering of Surfaces Defined by Implicit Functions.*" Rtqeggf kpi u" qh" yj g" CUOG" 8yj " Cppwcn' U{o r qukwo "" qp" J cr vku" kpgt hregu" hqt" Xktwcn' Gpxkqpo gpv' cpf" Vgrqr gtcvqt"" U{ ugo u."F cmcu."VZ."r r 083/8: .P qxgo dgt"3; ; 9"
 "
-]8: _ Uerkuwt{."LMO"Utkkxcucp."O 0C0"*Projects in VR.*"KGG."3; ; 9"
 "
-]8; _ Uco gv."J 0" Ur cvkcn' f cvc" ut wewtgu<"*Quadtree, Octrees and Other Hierarchical Methods.*"Cf f kuqp"Y gurg{."3; ; ; "
 "
-]92_ Ugf gh"O0"Uco vt"G0"Dcuf qi cp."E0"*Visual and Haptic Simulation of Linear Viscoelastic Tissue Behavior Based on Experimental Data.*" 4228"
 "
-]93_ Ugpqt."D0"Y qto crf ."R0"Eco r dgm" K0"*Evaluating a Haptic Modelling System with Industrial Designers,* GwtqJ cr vku"4224".4224"
 "
-]94_ Ugpqt."D0"Qgf i rg{."Q0"Y qto crf ."R0"Eco r dgm"K0"*Incorporating the FreeForm Haptic Modeling System into New Product Development,*" GwtqJ cr vku"4225."4225" "
 "
-]95_ UgpuCdrq"Vgej pqmji kgu."*OPENHAPTICS TOOLKIT version 2.0 API Reference.*"4227"
 "
-]96_ UgpuCdrq" Vgej pqmji kgu." *OPENHAPTICS TOOLKIT version 2.0 Programmer's Guide.*"4227"
 "
-]97_ UgpuCdrq."SensAble."[y y Ugpucdrq&eqo](#) ".Cwi wuv"45."4229"
 "

- 198_ Utkpxcucp." O 0C0" Dcuf qi cp." E0" *Haptic in Virtual Enviroments: Taxonomy.*" Tgugctej "Ucwwu." Cpf "Ej cngpi g." Ego r w0' ("I tcr j leu." Xqf03." P q06." r r 05; 5/626." 3; ; 9"
- "
- 199_ U{o dqre'Ego r wcvkqp'kphqto cvkqp'Egpygt. "*****" *SymbolicNet.*" [j wr <1y y y 0{ o dqrepgv0ti lctgcull Dacpf aEUli tqgdpqt0 vo ri.](#)" Lxmi34." 4229"
- "
- 19: _ V0' Mgucxcf cu." V0" Ecppqp." F 00" *Virtual Tools with Attributes for Robotic based Intermediate Manufacturing Processes.*" KGGG." Cr tki'3; ; 8"
- "
- 19: _ Vcpene." C0" J ktqc." M0" Mcpgmq." V0" *Virtual Cutting with Force Feedback.*" Xktwcn' Tgcirk' Cppwcn' kpygtpcvkpcn' U{o r qukwo ." r r 0369: 03; ; :
- "
-]: 2_ Vj qo cu." I 0" Lqj puqp" N0" F qy "U0" Ucpfhqtf " E0" *The Design and Testing of a Force Feedback Dental Simulator,*" Ego r wgt " O gj qf " cpf 'Rtqi tco u" k' Dkqo gf lekpg." 4222"
- "
-]: 3_ Vj qo cu." U0" Ueqw." R0" *Free Form Deformation of Solid Geometric Models, SK I TCRJ .*" Cuuqekvkqp'qh'Ego r wkpi "O cej kpgt { 0'Xqmw g" 42." P wo dgt '6." r ci g" 373/37; .3; ; 8"
- "
-]: 4_ Wpkxgtuk' qh' P qty 'Ectqrkpc." *RAPID.*" [j wr <1y y y 0u0pe0f wci gqo IQDDIQDDV0 vo ri.](#)" Cwi wuv'4: ." 4229"
- "
-]: 5_ Y cpi ." F 0" \ j cpi ." [0" Y cpi ." [0" Ngg." [0' U0" Nw." R0' cpf " Y cpi "[0" *Cutting on triangle mesh:" Local model-based haptic display for dental preparation surgery simulation.*" KGGG" Vtcpucevqpu" qp" Xkwwcn' cvkqp" cpf "" Ego r wgt "I tcr j leu." Xqf033." P q08." r ci g" 893/ 8: 5." 4227"
- "
-]: 6_ [cw." J 0" J uw." E0" *Development of a Dental Training System Based on Point-Based Model, Computer Aided Design & Applications.*" Xqf05." P q08." r ci g" 99; /9: 9." 4228"
- "
-]: 7_ \ j gpi {k" [0" [qpi j wc." E0" *Haptic Rendering of Milling.*" O gej cpxcn' Gpi kpggtkpi 'F gr ctvo gpv." 4224"
- "
-]: 8_ \ kngu." E00" Ucrkudwt {." L0M0" *A Constrained-based God-object Method For Haptic Display.*" CUO G" J cr vte" kpygtkcegu" hqt" Xktwcn' Gpxkqpo gpv" cpf "Vgrqqr gtcvqt "U{ ugo u." r ci g" 368/3720; ; 6"
- "

APPENDIX A

HARDWARES



Specifications for the PHANTOM® Omni™ haptic device

The SensAble Technologies PHANTOM® product line of haptic devices makes it possible for users to touch and manipulate virtual objects. Different models in the PHANTOM product line meet the varying needs of both research and commercial customers. The PHANTOM Premium models are high-precision instruments and within the PHANTOM product line provide the largest workspaces and highest forces, and some offer 6DOF capabilities. The PHANTOM Desktop and PHANTOM Omni models offer affordable desktop solutions. Of the two devices, the PHANTOM Desktop device delivers higher fidelity, stronger forces, and lower friction, while the PHANTOM Omni device is the most cost-effective haptic device available today. Below are the specifications for the PHANTOM Omni haptic device.



Model	The PHANTOM Omni Device
Force feedback workspace	~6.4 W x 4.8 H x 2.8 D in > 160 W x 120 H x 70 D mm
Footprint Physical area the base of device occupies on the desk	6 5/8 W x 8 D in ~168 W x 203 D mm
Weight (device only)	3 lb 15 oz
Range of motion	Hand movement pivoting at wrist > 450 dpi
Nominal position resolution	~ 0.055 mm
Backdrive friction	<1 oz (0.26 N)
Maximum exertable force at nominal (orthogonal arms) position	0.75 lbf. (3.3 N)
Continuous exertable force (24 hrs.)	> 0.2 lbf. (0.88 N)
Stiffness	X axis > 7.3 lb/in (1.26 N/mm) Y axis > 13.4 lb/in (2.31 N/mm) Z axis > 5.9 lb/in (1.02 N/mm)
Inertia (apparent mass at tip)	~0.101 lbm (45 g)
Force feedback	x, y, z
Position sensing	x, y, z (digital encoders)
..... [Stylus gimbal] [Pitch, roll, yaw (± 5% linearity potentiometers)]
Interface	IEEE-1394 FireWire® port
Supported platforms	Intel-based PCs
GHOST® SDK compatibility	No
3D Touch™ SDK compatibility	Yes
Applications	Selected Types of Haptic Research and The FreeForm® Concept™ system

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**SPECIFICATIONS COMPARISON FOR THE
PHANTOM® PREMIUM 1.5/6DOF & 1.5 HIGH FORCE/6DOF HAPTIC DEVICES**



	PHANTOM Premium 1.5/6DOF		PHANTOM Premium 1.5 High Force/6DOF	
Workspace	Translational	15 W x 10.5 H x 7.5 D inches 381 W x 267 H x 191 D mm	Translational	15 W x 10.5 H x 7.5 D inches 381 W x 267 H x 191 D mm
	Rotational Yaw Pitch Roll	297 degrees / 5.18 radians 260 degrees / 4.54 radians 335 degrees / 5.85 radians	Rotational Yaw Pitch Roll	297 degrees / 5.18 radians 260 degrees / 4.54 radians 335 degrees / 5.85 radians
Footprint	13 W x 10 D inches / 330 W x 254 D mm		13 W x 10 D inches / 330 W x 254 D mm	
Range of motion	Lower arm movement pivoting at elbow		Lower arm movement pivoting at elbow	
Nominal position resolution	Translational	860 dpi / 0.03mm	Translational	3784 dpi / 0.007 mm
	Rotational Yaw & Pitch	0.0023 degrees 0.00004 radians	Rotational Yaw & Pitch	0.0023 degrees 0.00004 radians
	Roll	0.0080 degrees 0.00014 radians	Roll	0.0080 degrees 0.00014 radians
Backdrive friction (x, y, z)	0.15 oz / 0.04 N		0.75 oz / 0.2 N	
Maximum exertable force and torque at nominal position (orthogonal arms)	Translational	1.9 lbf / 8.5 N	Translational	8.4lbf / 37.5N
	Rotational Yaw & Pitch Roll	73 oz-in / 515 mNm 24 oz-in / 170 mNm	Rotational Yaw & Pitch Roll	73 oz-in / 515 mNm 24 oz-in / 170 mNm
	Continuous exertable force and torque at nominal position (orthogonal arms)	0.3 lbf / 1.4 N 27 oz-in / 188 mNm 7 oz-in / 48 mNm	1.4 lbf / 6.2N 27 oz-in / 188 mNm 7 oz-in / 48 mNm	
Stiffness	20 lbf in ⁻¹ 3.5 N mm ⁻¹		20 lbf in ⁻¹ 3.5 N mm ⁻¹	
Inertia (apparent mass at tip)	< 0.30 lbm < 136 g		< 0.46 lbm < 210 g	
Weight (device only)	~ 20 lb ~ 9 Kg		~ 20 lb ~ 9 Kg	
Force feedback	x, y, z, Tx, Ty, Tz		x, y, z, Tx, Ty, Tz	
Position sensing	x, y, z, roll, pitch, yaw		x, y, z, roll, pitch, yaw	
Interface	Parallel port		Parallel port	
Supported Platforms	Intel-based PCs		Intel-based PCs	
GHOST® SDK Compatibility	Yes		Upon special request	
OpenHaptics™ Toolkit Compatibility	Yes		Yes	

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APPENDIX B

WAVEFRONT FILE FORMAT

"

The following text is describing of the .obj file:

Comment Line: "Nkpg'ku'c'eqo o gpv'wpxk'vj g'gpf 'qh'vj g'rkpg'"

some text

"

A single vertex's geometric position in space: "Vj g'htuv'xgtvz'rkuvf 'lp'vj g'hrj'j cu"

kpz g'z'3.'cpf 'uwdugs wgpv'xgtvz'gu'ctg'pwo dgtgf 'ugs wgpvkm{ 0'

v float float float

"

A texture coordinate: "Vj g'htuv'vzwtg'eqqf kpcv'lp'vj g'hrj'ku'kpz g'z'3.'cpf "

uwdugs wgpv'vzwtg'gu'ctg'pwo dgtgf 'ugs wgpvkm{ 0'Vj g'pwo dgt 'qh'vzwtg'eqqf kpcv'

f qgu'pqv'p'ggf 'v'q'o cvej 'vj g'pwo dgt 'qh'xgtvz'gu'0'

vt float float

A vertex normal: "Vj g'htuv'pqto cnl'lp'vj g'hrj'ku'kpz g'z'3.'cpf 'uwdugs wgpv'pqto cnu'ctg'"

pwo dgtgf 'ugs wgpvkm{ 0'

vn float float float

"

A face element: "Wukpi 'v.'vt.'cpf 'vn'v'q'tgr t'g'gpv'i gqo g'v'ke'xgtvz'gu.'vzwtg'xgtvz'gu."

cpf 'xgtvz'pqto cnu.'vj g'uv'go gpv'y qwf 't'gcf '<'"

f v/vt/vn v/vt/vn v/vt/vn v/vt/vn

Kl'vj g'g'ctg'qpn' 'xgtvz'gu'cpf 'xgtvz'pqto cnu'ht'c'hc'eg'grgo gpv'*pq'vzwtg'xgtvz'gu.:"

{ qw'y qwf 'gpvt'v' q'ur'uj gu'*1+0Hq't'gzco r'rg.'v'ur'gek' { 'qpn' 'vj g'xgtvz'cpf 'xgtvz' "

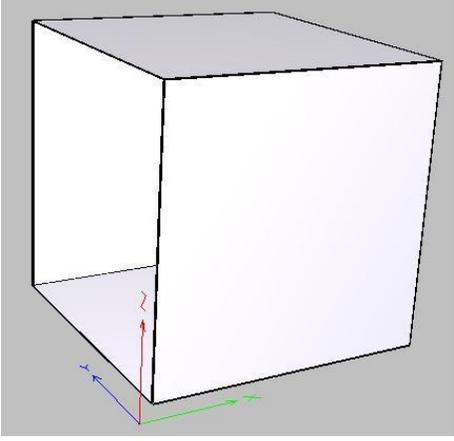
pqto cnu'gh'gt'g'peg'pwo dgtu.'{ qw'y qwf 'gpvt'<

"" ""h'3'1B'4'14'5'15'6'16"

"

"

VCDNG'D08'Ewdg'gzco r ng'lp'00QDL0'Hqto cv'

<pre> o vnd"ewdg0b vi' %qdlgev'Qdlgev%2" i "Qdlgeva a2" x"3"3"3" x"3"3"/3" x"3"3"/3" x"3"3"/3" x"/3"3"3" x"/3"3"/3" x"/3"3"/3" x"/3"3"/3" %: "xgtvleku" xp"3"2"2" xp"2"/3"2" xp"2"2"3" %5"pqto cni" wugo viGzr mtgtaF ghcwn' h"3 1B"5 1B"6 1B"4 1B" h"7 1B"9 1B": 1B"8 1B" h"3 14"7 14"8 14"4 14" h"5 14"9 14": 14"6 14" h"3 15"7 15"9 15"5 15" h"4 15"8 15": 15"6 15" </pre>	 <p>Hki wtg'D08" Ewdg'gzco r ng'lp'00QDL0'Hqto cv'</p> <p>"</p>
<pre> pgy o viGzr mtgtaF ghcwn' M: 2039869"2039869"2039869" Mf"2074; 63"2074; 63"2074; 63" Mu"2074; 63"2074; 63"2074; 63" kmo "4" Pu": " " " " O VN'hkg'qh'Ewdg'gzco r ng'qh'00QDL0'hqto cv' </pre>	

MTL file format

```

"
Cp"QDL'hkg'o c{ "f ghkg"cpf "ceeg uu"cp"gzvtpcn'O VN'hkg."y j lej "eqpvkpu" f ghpkkqpu"
qh"xctkqwu"o cvgtkcn'v{ r gu0Cp"O VN" hkg"ku"cp"cwzkrkt { "hkg"eqpvkpkpi "f ghpkkqpu"qh'
o cvgtkcn'v'j cv'o c{ "dg"ceeguugf "d{ "cp"QDL'hkg0Vj g"QDL'hkg"o wuv'ur gekh{ "j g"pco g"
qh'v'j g"O VN'hkg"d{ "c"eqo o cpf "uwej "cu="
"*****mltlib file_name
"
K' ku" r tguwo gf " j cv" v'j g" O VN" hkg" pco gu" cpf " f ghkgu" xctkqwu" o cvgtkcn. "uwej "cu."
r gtj cr u." $uj kp { tgf "$qt "$kqp$0Vj gp. "y kj kp" v'j g" QDL'hkg. "v'j g" eqo o cpf "lpf kcvgu" v'j cv"
cm' uwdugs wpgpeg "hcegu" uj qwf "dg" tgpf gtgf "y kj "v'j ku" o cvgtkcn "wpkri" c" pgy " o cvgtkcn" ku"
kpxqmgf 0"
"*****usemtl shinyred
"

```

Cp"O VN"hg"eqpvc"pu"u"ugs wpeg"qh"fg"hpkk"pu"qh'o cvgtkn0Gcej "f ghpkkp"dgi kpu"
y kj "c"newmtl""ucvgo gpv"vj cvf ghpgu"vj g'pco g"qh"vj g'o cvgtkn"hmjy gf "d{"hpgu"
ur gekh{ kpi "r ctvwrt "r tqr gtvgu0"

"

MTL File Characteristics:

"

CUE Ego o gpv" dgi kpu"y kj "c" %' ej ctcevt" kpu" eqnw p" 30 Drcpn"hpgu" o c{" dg"
kpu"gtvgf "hqt"erctk{ 0Qvj gty kug. "vj g"hg"eqpuku"qh"u"ugs wpeg"qh"newmtl"ucvgo gpv."
hmjy gf "d{"c" f ghpkkp"qh"xctkwa"r tqr gtvgu" hqt "vj cv'o cvgtkn0"

The quantities that may be defined for a material include:

Ka r g b = f ghpgu"vj g"co dpgv"eqmt"qh"vj g"o cvgtkn"vq"dg"*t.i .d+0Vj g"f ghcwn"ku"
*20.20.20 ="

"

Kd r g b? "f ghpgu"vj g"f hhwg"eqmt"qh"vj g"o cvgtkn"vq"dg"*t.i .d+0Vj g"f ghcwn"ku"
*20 .20 .20 ="

"

Ks r g b? "f ghpgu"vj g"ur gewrt"eqmt"qh"vj g"o cvgtkn"vq"dg"*t.i .d+0Vj ku"eqmt"uj qy u"wr "
kpu"j ki j rki j u0Vj g"f ghcwn"ku"*30.30.30 ="

"

d alpha? "f ghpgu"vj g"vcpur ctgpe{"qh"vj g"o cvgtkn"vq"dg"cr j c0Vj g"f ghcwn"ku"30"*pqv"
vcpur ctgpv"cv"cm+Uqo g"hqto cw"wg"Vt"kpugcf "qh"Vt="

"

Tr alpha? "f ghpgu"vj g"vcpur ctgpe{"qh"vj g"o cvgtkn"vq"dg"cr j c0Vj g"f ghcwn"ku"30"
*pqv"vcpur ctgpv"cv"cm+Uqo g"hqto cw"wg"Vt"kpugcf "qh"Vt="

"

Ns s? "f ghpgu"vj g"uj kpgu"qh"vj g"o cvgtkn"vq"dg"u0Vj g"f ghcwn"ku"20 ="

"

illum n? "f gpqvu"vj g"knwo kpcvqp"o qf grlvugf "d{"vj g"o cvgtkn0 knwo "? "3"kp f kcvgu" c"
hrv'o cvgtkn"y kj "pq"ur gewrt"j ki j rki j w. "uq"vj g"xcnwg"qh"Ks"ku"pqv"wgf 0knwo "? "4"
f gpqvu"vj g"r tugpeg"qh"ur gewrt"j ki j rki j w. "cpf "uq"u"ur gekh"ecvqp" hqt "Ks"ku"tgs vkt gf 0"

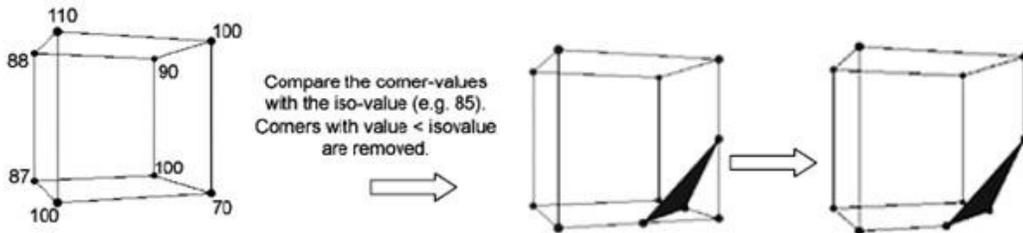
"

"

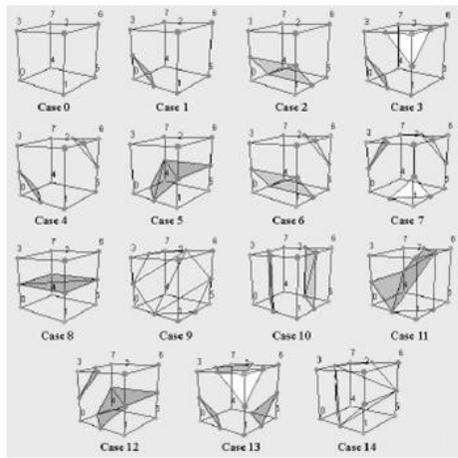
APPENDIX C

MARCHING CUBES

"
 " f g x g r g f " c r r d e c v k p . " v j g " f c v c u g v " k u " k o r n g o g p v g f " k p " c " o c v t k z " u t w e w t g " k p " y j k e j " v j g " q t k i k p c i " o c t e j k p i " e w d g u " c n i q t k j o " k u " c r r d k g f " h q t " f c v c " o c p c i g o g p v " c p f " h q t " i g p g t c v k p i " c " 5 F " o q f g n ' q h ' f g h q t o c d n g " o q f g n ' V j g " q d l g e v " k u " d w k u " w r " q h ' e w d g u " v j c v ' e q p u k u v " q h ' q p g " f g p u k v { " x c n w g " k p " g c e j " e q t p g t O F k h g t g p v " x g t v k e g u " c t g " e t g c v g f " c n q p i " v j g " g f i g u " q h " g c e j " e w d g " w u k p i " d k p g c t " k p v g t r q r c v k p p " f g r g p f k p i " q p " v j g " t g r c v k p u j k r " d g w g g p " v j g " x q z g n ' x c n w g u O C " p q t o c n i ' x g e v q t " k u " e c r e w r c v g f " h q t " g x g t { " x g t v g z O * H k i w t g " 8 0 6 + " Y j g p " c n i ' x g t v k e g u " c t g " c n g p " v q i g v j g t . " v j g " v t k p i n g u ' h q t o " v j g " u w t h c e g " q h ' v j g " q d l g e v O "



" H k i w t g " E 0 8 " V j g " v t k p i n g u ' h q t o " v j g " u w t h c e g " q h ' v j g " q d l g e v O * H k i w t g " 8 0 6 + " D c u g f " q p " v j g " x q z g n ' f g p u k v { " q h ' g c e j " x g t v g z . " v j g " p q t o c n i " q h ' v j g " v t k p i n g " c t g " e c r e w r c v g f " c p f " v j g u g " p q t o c n i " c t g " k p v g t r q r c v g f " v q " i k x g " c " u o q q v j " u w t h c e g O "



Hli wtg'E04" Vj g'37f hgtgpvr quidkklgu'vj cv'tkcpj ngu'ecp'dg'eqputwefg "

"

"