Bellcomm

955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

B71 09027

date: September 29, 1971

to: Distribution

from: S. Kaufman

subject: A Digital Program for Stability and Performance Characteristics of a Four-Wheel Vehicle - Case 320

ABSTRACT

An extension of the equations of motion of a four-wheel vehicle into the areas of electric motor propulsion and soil characteristics is presented. The primary motivation of this study was to extend the dynamic stability capability of the digital program ROVER for the Lunar Roving Vehicle into the area of vehicle performance.

Speed, power consumption, and loads characteristics of the Lunar Roving Vehicle were obtained for the vehicle traversing a simulated lunar soil at full throttle along a straight course. Four terrain roughness were considered: an upper range rough mare, a middle range rough mare, a middle range smooth mare, and a perfectly smooth terrain. For each soil roughness two computer runs were made: one based on optimistic soil, wheel and motor characteristics and the other based on pessimistic characteristics. The optimistic characteristics appear to be the better data based on findings of the Apollo 15 mission.

X71-83365
(ACCESSION NUMBER) (THRU)
30 None
(PAGES) (CODE)
CR-123223
(NASA CR OR TMX OR AD NUMBER) (CATEGORY)
FF No. 602(A)
AVAILABLE TO NASA OFFICES AND NASA RESEARCH CENTERS ONLY

NOV 1971 RECEIVED NASA STI FACILITY INPUT BRANCH

(NASA-CR-123223) A DIGITAL PROGRAM FOR STABILITY AND PERFORMANCE CHARACTERISTICS OF A FOUR-WHEEL VEHICLE (Bellcomm, Inc.) 30 p

N79-72033

Unclas
00/14 12128

Bellcomm

955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

B71 09027

date: September 29, 1971

to: Distribution

from: S. Kaufman

subject: A Digital Program for Stability and Performance Characteristics of a Four-Wheel Vehicle - Case 320

MEMORANDUM FOR FILE

INTRODUCTION

The equations of motion plus the digital program ROVER of a four-wheel vehicle was presented in References 1 and 2. This vehicle has independent suspension and may be powered by individual wheel electric motors as it traverses a deterministic terrain defined by slopes, bumps, craters, and/or a random terrain. The primary motivation of ROVER was to ascertain the dynamic stability of the Lunar Roving Vehicle (LRV) with some emphasis (Reference 2) on performance of the LRV. The current report is essentially an update of ROVER, mainly in the area of performance. Most of the emphasis of this report is placed on the incorporation of the electric motor and lunar soil characteristics into the equations of motion. Other minor additions and improvements have been made in areas such as cornering forces, washboard terrain, and suspension characteristics. All of the additions to ROVER along with the existing input are given in the Appendix of this report.

Motor Characteristics

The series motor model of Reference 1 has been modified as follows:

$$\left.\begin{aligned} \frac{VOLT - (i)(RFIX + REV)}{CONMEG(\omega)i^{a}} &= F(\omega) \\ \frac{T_h}{DCON(i)^{CMOT}} &= F(i) \\ T_d &= T_h - TFR \end{aligned}\right\} \text{for } \omega \geq C\phi P \qquad (1)$$

where

VOLT = battery voltage

i = quasi-static current

a = CMOT - 1

RFIX = fixed resistance

REV = variable resistance

ω = angular wheel velocity

CONMEG, DCON, CMOT = constants

T_h = motor torque delivered to wheel plus motor-transmission losses

TFR = frictional torque (motor-transmission losses)

$$F(\omega) = \sum_{j=0}^{IPP-1} b_j \omega^j$$

$$F(i) = \sum_{j=0}^{IPP-1} c_j \omega^j$$

$C\phi P$ = minimum value of ω, and

T_d = torque delivered by motor.

To keep F(i) from becoming multivalued, Equation (1) is applicable for $\omega \geq C\phi P$ (see Figure 1 for the current-omega relationahip for $\omega < C\phi P$). In ROVER, $C\phi P$ is given for the full throttle condition (REV = 0) and, therefore, Equation (1) is only an approximation for other than a full throttle condition. This generally imposes no real hardship for the LRV as COP is less than 3.50 radians per second (less than 5 km/hr forward speed), below normal operating speeds.

If a wheel becomes airborne, the angular velocity at time step k is estimated from the torque at the previous time step (k-1) as follows:

$$\omega_k = \omega_{k-1} + (\Delta_k) T_{a(k-1)}/TIN \qquad (2)$$

where Δ_k is the time interval, T_a is useable torque (to be subsequently explained, Equation 6), and TIN is the mass moment of inertia of the rotating parts.

Soil Characteristics

The soil characteristics are obtained simultaneously with the motor characteristics. From the useable motor torque at the previous time step a torque number $TN\phi$ is calculated as follows:

$$TN\phi = T_{a(k-1)} \times c/RE \times P \qquad (3)$$

where

RE = torque radius = wheel radius - 1/2 tire deformation,

P = suspension force noraml to ground, and

c = ratio of spring mass to total mass.

A slip number is computed as a polynomial of order NP-1 of the torque number as follows:

$$SN\phi = \sum_{j=0}^{NP-1} d_j (TN\phi)^j \quad . \tag{4}$$

From the forward velocity of a wheel (AVI)ω is computed as follows

$$\omega = AVI/R\phi(1 - SN\phi) \quad , \tag{5}$$

where $R\phi$ = roll radius. Next the current and torque are obtained from Equation (1). The power loss due to cornering and damping are next obtained and divided by ω to obtain an equivalent torque loss T_ℓ. The useable torque T_a is next as follows:

$$T_a = T_d - T_\ell \quad . \tag{6}$$

The torque number can now be updated (Equation 3) and a pull number ($PN\phi$) computed as a polynomial of the torque number, or

$$PN\phi = \sum_{j=0}^{NP-1} e_j (TN\phi)^j \quad . \tag{7}$$

The propulsion force (F) for one of the wheels is finally obtained as

$$F = PN\phi \times P \quad . \tag{8}$$

Sample Problems

Speed, power consumption, and load characteristics of the LRV were obtained for the vehicle traversing a simulated lunar soil at full throttle on a straight course. Four terrain roughness were considered: a perfectly smooth lurain, a middle range smooth mare, a middle range rough mare, and an upper range rough mare. Two runs were made for each roughness. One run was based on optimistic motor and soil characteristics and a computed roll radius equal to the undeformed wheel minus instantaneous tire deformation. The second run was based on pessimistic motor and soil characteristics and a roll radius equal to 13.57 inches. The optimistic soil data (lunar soil simulant LSS_4) was obtained from the spread of data from Figure 16 of Reference 3 (add 0.1 to the torque coefficients of Figure 16). The pessimistic soil data was based on a consensus of WES (U. S. Army Engineer Waterway Experimental Station) and MSFC. The optimistic motor characteristics were obtained from Boeing-Huntsville and the pessimistic data obtained from MSFC. The optimistic roll radius was programmed by the author and the pessimistic one based on a consensus of WES and MSFC. The lurain PSD are smoothed data generated by Dr. R. Pike of USGS (Figures 5 - 8 of Reference 4). Most of the remaining data was obtained from Boeing-Huntsville.

The input for the optimistic runs are given in Figures 2 - 5; the input for the pessimistic runs are given in Figures 6 - 9. The mechanical units are in pounds, inches, seconds; the electrical units are volts, amperes, ohms. The results of the optimistic and pessimistic runs are summarized in Tables I and II, respectively. Based on findings of the Apollo 15 mission (12 - 13 km/hr maximum speed on level lurain and a consumption rate of 65 - 70 watt-hr per kilometer traveled), the optimistic characteristics appear to be the better data.

S. Kaufman

2031-SK-jf

S. Kaufman

Attachments

TABLE I

SUMMARY OF COMPUTER RUNS - LUNAR ROVING VEHICLE - OPTIMISTIC

	SMOOTH LURAIN	MID-RANGE SMOOTH MARE	MID-RANGE ROUGH MARE	UPPER-RANGE ROUGH MARE
Initial Velocity - KM/HR	13.0	13.0	9.0	8.0
Average Velocity - KM/HR	13.4	13.0	9.1	7.3
Maximum Velocity - KM/HR	13.4	13.2	9.7	8.8
Minimum Velocity - KM/HR	13.0	12.7	8.6	5.9
Elapsed Time - Seconds	68.0	32	32	32
Distance Traversed - KM	.252	.115	.081	.065
Total Energy Consumed - WATT HR	16.3	8.38	10.5	13.8
Consumption Rate - WATT/KM	65	73	130	213
Maximum Suspension Force - LBS	61	148	250	686
Maximum Acceleration - Earth G's	--	.10	.16	.67
*Fraction Wheel Off Ground	--	.01	.15	.30
*Motor Power - WATT	86	109	145	203
*Damper Power - WATT	--	8	17	26
*Cornering Power - WATT	--	2	8	16

*Average Per Wheel Over Distance Traversed

TABLE II

SUMMARY OF COMPUTER RUNS - LUNAR ROVING VEHICLE - PESSIMISTIC

	SMOOTH LURAIN	MID-RANGE SMOOTH MARE	MID-RANGE ROUGH MARE	UPPER RANGE ROUGH MARE
Initial Velocity - KM/HR	10.0	10.0	8.0	7.0
Average Velocity - KM/HR	9.6	9.4	7.7	6.0
Maximum Velocity - KM/HR	10.0	10.0	8.4	7.4
Minimum Velocity - KM/HR	9.6	8.9	7.0	3.6
Elapsed Time - Seconds	72	32	32	32
Distance Traversed - KM	.192	.0823	.0687	.0531
Total Energy Consumed - WATT HR	17.9	8.33	10.43	16.8
Consumption Rate - WATT HR/KM	93	101	152	316
Maximum Suspension Force - POUNDS	60**	115	187	530
Maximum Acceleration - EARTH G's	--	.07	.12	.45
*Fraction Wheel Off Ground	--	--	.13	.26
*Motor Power - WATT	92	100	144	196
*Damper Power - WATT	--	4.3	13.4	22
*Cornering Power - WATT	--	1.0	5.3	14.5

*Average Per Wheel Over Distance Traversed

**1-G Moon Gravity

FOR $\omega < COP$ $i = i\,(COP) + SLOPE\,(COP - \omega)$

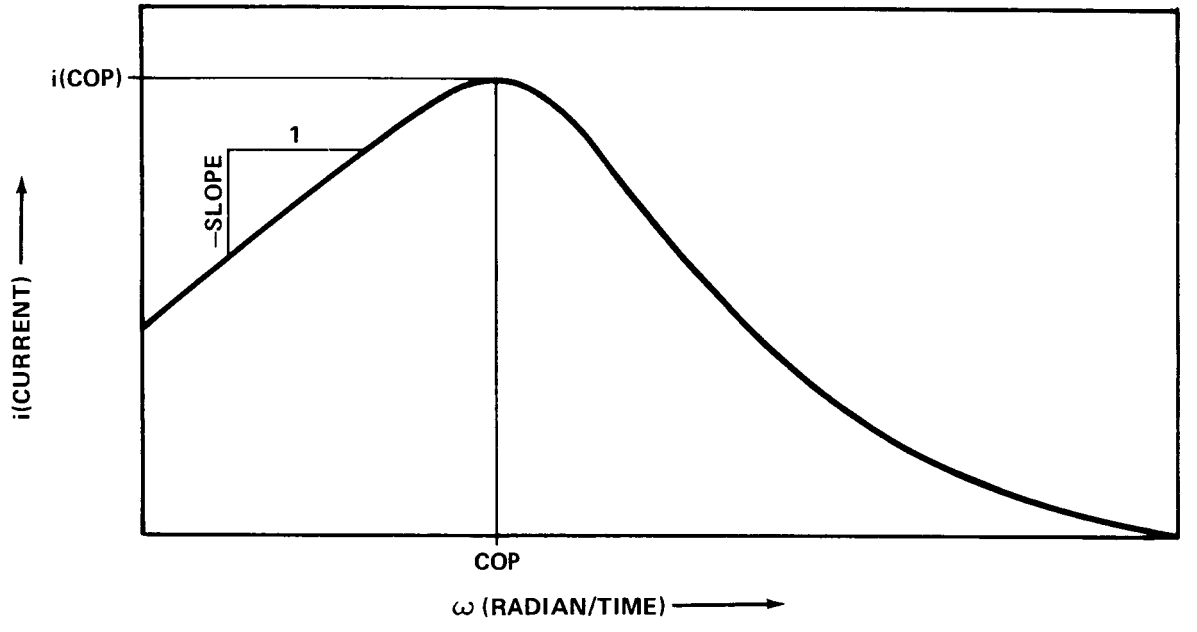

FIGURE 1 - CURRENT VERSUS WHEEL SPEED CHARACTERISTICS

Figure 2

SMOOTH TERRAIN

```
XQT          SK3190.ABS
CURK=4*4.
PHI=90.0,PSI=-90.0,THETA=-.26,
RW=16.,WM=26.,CM=386.,GM=61.8,T1N=13800.,Y=1433.,535000.,1650000.,1670000.,
NINT=25000,DELTIM=.050,IPRT=80,
SF=.6,VSE=5.,
N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
SIR=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
NDOT=3,K=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
VBRAK=5.,NTRIM=1,
COMMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
NST=4*1,UNIT=1.        ,RF=.6,NSFRMO=1,
CMOT=1.1,
MST=4*1,POWIN=60.,
NGUID=1,XGD=40000.,YGD=    0.,VCR=50.          ,CONS=4*100.          ,ACR=200.,
LP=2,CUC=1.,22.,RVRB=40.,2.,
NEL=500 ,XRAN= 5.,
U=142.1,VGD=180.,
RVPA=3600.             ,REMAX=3600.,AST=22.,VOLT=36.,
NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
 VEL=-.05,.08,.23,.34,.66,
PNO=-.100,0.000,.150,.200,.500,TORQ=-.05,.0,.05,.1,.6,
PERC=.31,DPER=.31,
OGVE=10.45,8.35,7.22,6.28,5.23,3.45,GORQ=152.,227.,292.,397.,547.,1057.,
IPP=6,AMPE=4.2,6.6,7.8,9.8,12.6,21.6,COP=3.45,
VCOUL=2.,
$END
```

Figure 3

MIDDLE RANGE SMOOTH MARE

```
@  XQT          SK3190.ABS
  CURR=4*4,
  PHI=90.0,PSI=-90.0,THETA=-.26,
  RW=16.,WM=26.,CM=386.,GM=61.8,TIN=13800.,Y=1433.,535000.,1650000.,1670000.,
  NINT=1281 ,DELTIM=.025,IPRT=80,
  SF=.6,VSE=5.,
  N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
  SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
  SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
  SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
  Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
  NDOT=3,R=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
  VBRAK=5.,NTRIM=1,
  CONMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
  NCF=58,
  CFR=    .0429 ,.0393 ,.0362 ,.0336 ,.0312 ,.0286 ,.0257 ,.0237 ,.0216 ,
  .0196 ,.0181 ,.0165 ,.0150 ,.0135 ,.0122 ,.0112 ,.0105 ,.0095 ,.0084 ,
  .0081 ,.00765,.00713,.00662,.00612,.00560,.00510,.00472,.00406,.00378,
  .00346,.00321,.00295,.00272,.00250,.00230,.00212,.00194,.00178,.00163,
  .00150,.00138,.00127,.00117,.00110,.00102,.00093,.000865,.00079,.00074,
  .00069,.000635,.000585,.000555,.00051,.000473,.000408,.00038,.000346,
  AMC=.0235,.0224,.0206,.0203,.0219,.0235,.0237,.0227,.025,.024,.0234,.0242,
  .028,.03,.028,.0274,.0258,.028,.033,.0312,.0312,.0375,.0437,.05,.0582,
  .0686,.1,.102,.078,.086,.102,.133,.183,.212,.222,.241,.253,
  .282,.345,.415,.492,.625,.765,.795,.938,1.12,1.40,1.36,1.31,1.53,
  1.62,1.64,1.52,1.64,2.24,2.23,1.5,1.5,
  NST=4*1,UNIT=1.      ,BF=.6,NSERMO=1,
  CMOT=1.1,
  MST=4*1,POWIN=60.,
  NGUID=1,XGD=40000.,YGD=   0.,VCR=50.        ,CONS=4*100.        ,ACR=200.,
  LP=2,CUC=1.,22.,RVRB=40.,2.,
  NEL=500 ,XRAN= 5.,
  U=142.1,VGD=180.,
  RVRA=3600.          ,REMAX=3600.,AST=22.,VOLT=36.,
  NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
   VEL=-.05,.08,.23,.34,.66,
  PNO=-.100,0.000,.150,.260,.500,TORQ=-.05,.0,.05,.1,.6,
  PERC=.28,DPER=.28,
  IPP=6,AMPE=4.2,6.6,7.8,9.8,12.6,21.6,COP=3.45,
  OGME=10.45,8.35,7.22,6.28,5.23,3.45,GORQ=152.,227.,292.,397.,547.,1057.,
  VCOUL=2.,
  NDATA=1,
  $END
```

Figure 4

MIDDLE RANGE ROUGH MARE

```
@ XQT          SK3190.ABS
CURR=4.4,
PHI=90.0,PSI=-90.0,THETA=-.26,
RW=16.,WN=26.,CM=386.,GM=61.8,TIN=13800.,Y=1433.,535000.,1650000.,1670000.,
NINT=1281,DELTIM=.025,IPRT=80,
SF=.6,VSE=5.,
N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
NDOT=3,R=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
VBRAK=5.,NTRIM=1,
CONMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
NCF=58,
CFR=   .0429 ,.0393 ,.0362 ,.0336 ,.0312 ,.0286 ,.0257 ,.0237 ,.0216 ,
.0196 ,.0181 ,.0165 ,.0150 ,.0135 ,.0122 ,.0112 ,.0105 ,.0095 ,.0084 ,
.0081 ,.00765,.00713,.00662,.00612,.00560,.00510,.00472,.00406,.00378,
.00346,.00321,.00295,.00272,.00250,.00230,.00212,.00194,.00178,.00163,
.00150,.00138,.00127,.00117,.00110,.00102,.00093,.000865,.000790,.00074,
.00069,.000635,.000585,.000555,.00051,.000473,.000408,.00038,.000346,
AMC=  .0670,.070,.064,.065,.075,.090,.097,.094,.100,
.0983,.0935,.112,.14 ,.147,.14 ,.109,.117,.131,.164,
.173 ,.172 ,.187,.219,.234,.281,.328,.625,.810,.615,
.771 ,.86  ,1.19,1.41,1.72,1.87,2.12,2.34,2.81,3.0 ,
3.52 ,4.55 ,4.52,4.52,4.7 ,5.62,7.0 ,7.95,7.4 ,6.25,
6.87 ,7.8  ,7.37,6.55,6.8 ,9.35,8.95,6.0 ,5.65,
NST=4*1,UNIT=1.       ,BF=.6,NSERMO=1,
CMOT=1.1,
NST=4*1,POWIN=60.,
NGUID=1,XGD=40000.,YGD=   0.,VCR=50.        ,CONS=4*100.          ,ACR=200.,
LP=2,CUC=1.,22.,RVRB=40.,2.,
NEL=500 ,XRAN= 5.,
U=98.40,VGD=180.,
RVRA=3600.            ,REMAX=3600.,AST=22.,VOLT=36.,
NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
 VEL=-.05,.08,.23,.34,.66,
PNO=-.100,0.000,.150,.260,.500,TORQ=-.05,.0,.05,.1,.6,
PERC=.26,DPER=.26,
IPP=6,AMPE=4.2,6.6,7.8,9.8,12.6,21.6,COP=3.45,
OGME=10.45,8.35,7.22,6.28,5.23,3.45,GORQ=152.,227.,292.,397.,547.,1057.,
VCOUL=2.,
NDATA=1,
$END
```

Figure 5

UPPER RANGE ROUGH MARE

```
@ XQT          SK3190.ABS
CURR=4*4.
PHI=90.0,PSI=-90.0,THETA=-.26,
RW=16.,WM=26.,CM=386.,GM=61.8,TIN=13800.,Y=1433.,535000.,1650000.,1670000.,
NINT=1281,DELTIM=.025,IPRT=20,
SF=.6,VSE=5.,
N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
NDOT=3,R=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
VBRAK=5.,NTRIM=1,
CONMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
NCF=58,
CFR=   .0429 ,.0393 ,.0362 ,.0336 ,.0312 ,.0286 ,.0257 ,.0237 ,.0216 ,
.0196 ,.0181 ,.0165 ,.0150 ,.0135 ,.0122 ,.0112 ,.0105 ,.0095 ,.0084 ,
.0081 ,.00765,.00713,.00662,.00612,.00560,.00510,.00472,.00406,.00378,
.00346,.00321,.00295,.00272,.00250,.00230,.00212,.00194,.00178,.00163,
.00150,.00138,.00127,.00117,.00110,.00102,.00093,.000865,.000790,.00074,
.00069,.000635,.000585,.000555,.00051,.000473,.000408,.00038,.000346,
AMC=                                                    .304,.304,.274,.265,
.281,.297,.304,.279,.288,.252,.262,.311,.356,.361,.320,.273,.258,.280,.352,
.352,.312,.343,.437,.500,.594,.602,1.06,1.30,1.03,1.20,1.40,1.92,2.25,2.25,
2.34,3.28,4.05,4.68,5.15,5.45,5.62,6.25,7.65,7.96,9.37,11.7,15.4,15.6,14.02,
15.6,18.72,17.95,18.75,19.82,28.1,28.9,20.6,20.6,
NST=4*1,UNIT=1.      ,BF=.6,NSERMO=1,
CMOT=1.1,
MST=4*1,POWIN=60.,
NGUID=1,XGD=40000.,YGD=   0.,VCR=50.        ,CONS=4*100.        ,ACR=200.,
LP=2,CUC=1.,22.,RVRB=40.,2.,
NEL=500 ,XRAN= 5.,
U=87.50,VGD=180.,
RVRA=3600.          ,REMAX=3600.,AST=22.,VOLT=36.,
NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
 VEL=-.05,.08,.23,.34,.66,
PNO=-.100,0.000,.150,.260,.500,TORQ=-.05,.0,.05,.1,.6,
PERC=.24,DPER=.24,
IPP=6,AMPE=4.2,6.6,7.8,9.8,12.6,21.6,COP=3.45,
OGME=10.45,8.35,7.22,6.28,5.23,3.45,GORQ=152.,227.,292.,397.,547.,1057.,
VCOUL=2.,
NDATA=1,
$END
```

Figure 6

SMOOTH TERRAIN COSERVATIVE ROLL RAD CONSERVATIVE MOTOR LSS4

```
@ XQT          SK3190.ABS
 CURR=4*4;
 PHI=90.0;PSI=-90.0,THETA=-.26,
 RW=16.,WM=26.,CM=386.,GM=61.8,TIN=13800.,Y=1433.,535000.,1650000.,1670000.,
 NINT=25000,DELTIM=.050,IPRT=80,
 SF=.6,VSE=5.,
 N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
 SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
 SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
 SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
 Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
 NDOT=3,R=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
 VBRAK=5.,NTRIM=1,
 CONMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
 NST=4*1,UNIT=1.        ,BF=.6,NSFRMO=1,
 CMOT=1.1;
 MST=4*1,FOWIN=60.,
 NGUID=1,XGD=40000.,YGD=    0.,VCR=50.          ,CONS=4*100.          ,ACR=200.,
 LP=2,CUC=1.,22.,RVRB=40.,2.,
 NEL=500 ;XRAN= 5.,
 U=109.3,VGD=170.,
 RVRA=3600.            ,REMAX=3600.,AST=22.,VOLT=36.,
 NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
 VEL=-.03,.07,.21,.35,.66,
 PNO=-.123,-.035,.088,.211,.435,TORQ=-.05,.0.,.05,.1,.6,
 PERC=.31;OPER=.31,ROLLR=13.57
 OGME=9.4;8.35,7.31,6.28,5.24,3.,GORQ=137.,181.,251.,347.,485.,1057.,
 COP=3.,IPP=6,AMPE=4.,5.2,6.6,8.4,10.8,21.,
 VCOUL=2.;
 $END
```

Figure 7

MIDDLE RANGE SMOOTH MARE CONSERV RAD CONSERVATIVE MOTOR LSS4

```
@  XQT          SK3190.ABS
CURR=4*4.
PHI=90.0,PSI=-90.0,THETA=-.26,
RW=16.,WM=26.,CM=386.,GM=61.8,TIN=13800.,Y=1433.,535000.,1650000.,1670000.,
NINT=1281 ,DELTIM=.025,IPRT=80,
SF=.6,VSE=5.,
N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
NDOT=3,R=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
VBRAK=5.,NTRIM=1,
CONMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
NCF=58,
CFR=    .0429 ,.0393 ,.0362 ,.0336 ,.0312 ,.0286 ,.0257 ,.0237 ,.0216 ,
.0196 ,.0181 ,.0165 ,.0150 ,.0135 ,.0122 ,.0112 ,.0105 ,.0095 ,.0084 ,
.0081 ,.00765,.00713,.00662,.00612,.00560,.00510,.00472,.00406,.00378,
.00346,.00321,.00295,.00272,.00250,.00230,.00212,.00194,.00178,.00163,
.00150,.00138,.00127,.00117,.00110,.00102,.00093,.000865,.000790,.00074,
.00069,.000635,.000585,.000555,.00051,.000473,.000430,.00038,.000346,
AMC=.0235,.0224,.0206,.0203,.0219,.0235,.0237,.0227,.025,.024,.0234,.0242,
.028,.03,.028,.0274,.0258,.028,.033,.0312,.0312,.0375,.0437,.05,.0582,
.0686,.1,.102,.078,.086,.102,.133,.183,.212,.222,.241,.253,
.282,.345,.415,.492,.625,.765,.795,.938,1.12,1.40,1.36,1.31,1.53,
1.62,1.64,1.52,1.64,2.24,2.23,1.5,1.5,
NST=4*1,UNIT=1.        ,BF=.6,NSERHO=1,
CMOT=1.1,
MST=4*1,POWIN=60.,
NGUID=1,XGD=40000.,YGD=    0.,VCR=50.          ,CONS=4*100.          ,ACR=200.,
LP=2,CUC=1.,22.,RVRB=40.,2.,
NEL=500 ,XRAN= 5.,
U=109.3,VGD=180.,
RVRA=3600.             ,REMAX=3600.,AST=22.,VOLT=36.,
NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
VEL=-.03,.07,.21,.35,.66,
PHO=-.123,-.035,.088,.211,.435,TORQ=-.05,.0,.,.05,.1,.6,
PERC=.28,DPER=.28,ROLLR=13.57,
COP=3.,IPP=6,AMPE=4.,5.2,6.6,8.4,10.8,21.,
OGME=9.4,3.35,7.31,6.28,5.24,3.,GORQ=137.,181.,251.,347.,485.,1057.,
VCOUL=2.,
NDATA=1,
$END
```

Figure 8

MIDDLE RANGE ROUGH MARE CONSER RAD CONSERVATIVE MOTOR LSS4

```
@ XQT          SK3190.ABS
 CORR=4*4.
 PHI=90.0,PSI=-90.0,THETA=-.26,
 RW=16.,WM=26.,CM=386.,GM=61.8,TIN=13800.,Y=1433.,535000.,1650000.,1670000.,
 NINT=1281 ,DELTIM=.025,IPRT=80,
 SF=.6,VSE=5.,
 N50=0.,DAMC=2.,DAMP=4*.1525,COLUMB=4.,DAMW=1.,CEW=.21,
 SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
 SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
 SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
 Z=46.7,36.,-23.9,46.7,-36.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
 NDOT=3,K=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
 VBRAK=5.,NTRIM=1,
 COMMEG=2.155,DCON=32.,TFR=107.,RFIX=1.44,
 NCF=58,
 CFR=   .0429 ,.0393 ,.0362 ,.0336 ,.0312 ,.0286 ,.0257 ,.0237 ,.0216 ,
 .0195 ,.0181 ,.0165 ,.0150 ,.0135 ,.0122 ,.0112 ,.0105 ,.0095 ,.0084 ,
 .0081 ,.00765,.00713,.00662,.00612,.00560,.00510,.00472,.00406,.00378,
 .00346,.00321,.00295,.00272,.00250,.00230,.00212,.00194,.00178,.00163,
 .00150,.00138,.00127,.00117,.00110,.00102,.00093,.000865,.000790,.00074,
 .00069,.000635,.000585,.000555,.00051,.000473,.000408,.00038,.000346,
 AMC=  .0670,.070,.064,.065,.075,.090,.097,.094,.100,
 .0985,.0935,.112,.14 ,.147,.14 ,.109,.117,.131,.164,
 .173 ,.172 ,.187,.219,.234,.281,.328,.625,.610,.615,
 .771 ,.86  ,1.19,1.41,1.72,1.87,2.12,2.34,2.81,3.0 ,
 3.52 ,4.55 ,4.52,4.52,4.7 ,5.62,7.0 ,7.95,7.4 ,6.25,
 6.87 ,7.8  ,7.37,6.55,6.8 ,9.35,8.95,6.0 ,5.65,
 NST=4*1,UNIT=1.       ,BF=.6,NSERMO=1,
 CMOT=1.1,
 MST=4*1,POWIN=60.,
 NOSID=1,XGD=40000.,YGD=   0.,VCR=50.        ,CONS=4*100.        ,ACR=200.,
 LF=2,CUC=1.,22.,RVRB=40.,2.,
 NEL=500 ,XRAN= 5.,
 G=87.00,VGD=180.,
 RVRA=3600.          ,REMAX=3600.,AST=22.,VOLT=36.,
 NP=5,VMAX=.4,VMIT=-.03,CONV=8.854,
 VEL=-.03,.07,.21,.55,.36,
 PNO=-.123,-.035,.088,.211,.435,TORQ=-.05,.0.,.05,.1,.6,
 PERC=.26,DPER=.26,ROLLR=13.57,
 COP=3.,IPP=6,AMPL=4.,5.2,6.6,8.4,10.8,21.,
 OGME=9.4,8.35,7.31,6.28,5.24,3.,GORQ=137.,181.,251.,347.,485.,1057.,
 VCOUL=2.,
 MDATA=1,
 $END
```

Figure 9

```
UPPER  RANGE ROUGH  MARE CONSER RAD    CONSERVATIVE MOTOR LSS4

@  XQT          SK3190.ABS
 CURR=4.4,
 PHI=90.0,PSI=-90.0,THETA=-.26,
 RA=16.,RM=26.,CM=385.,GR=61.8,TIN=13800.,Y=1433.,535000.,165000.,1670000.,
 NINT=1281  ,DELTIM=.025,IPRT=20,
 SE=.,,VSC=5.,
 NSO=0.,DAMC=2.,DAMP=4.1525,COLUMN=4.,DAMN=1.,CEN=.21,
 SL=10.,3.0,12.5,10.,3.0,12.5,10.,3.0,12.5,10.,3.,12.5,
 SIA=600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,600.,53.0,12.0,
 SIB=600.,136.,136.,600.,136.,136.,600.,136.,136.,600.,136.,136.,
 Z=46.7,36.,-23.9,46.7,-35.,-23.9,-43.3,-36.,-23.9,-43.30,36.,-23.9,
 NDOT=3,R=0.,0.,0.,-7.3,14.5,0.,-7.3,-14.5,0.,
 VBRAK=5.,NTRIM=1,
 COMMEG=2.155,DCON=32.,TFR=107.,REIX=1.44,
 NCF=58,
 CFR=    .0429 ,.0393 ,.0362 ,.0336 ,.0312 ,.0286 ,.0257 ,.0237 ,.0216 ,
 .0196 ,.0181 ,.0165 ,.0150 ,.0135 ,.0122 ,.0112 ,.0105 ,.0095 ,.0084 ,
 .0081 ,.00765,.00713,.00662,.00612,.00560,.00510,.00472,.00406,.00371,
 .00346,.00321,.00295,.00272,.00250,.00230,.00212,.00194,.00178,.00163,
 .00150,.00138,.00127,.00117,.00110,.00102,.00093,.000865,.000790,.00074,
 .00069,.000635,.000585,.000555,.00051,.000473,.000408,.00038,.000346,
 AMC=                                                    .304,.304,.274,.265,
 .281,.297,.304,.279,.288,.252,.262,.311,.355,.361,.320,.273,.253,.280,.352,
 .352,.312,.343,.437,.500,.574,.602,1.06,1.30,1.03,1.20,1.40,1.92,2.25,2.25,
 2.34,3.28,4.05,4.68,5.15,5.45,5.62,6.25,7.65,7.96,9.37,11.7,15.4,15.6,14.02,
 15.6,18.72,17.95,18.75,19.82,28.1,28.9,20.6,20.6,
 NST=1*1,UNIT=1,        ,RF=.6,NSERMO=1,
 CMOT=1.1,
 MST=4*1,POWER=60.,
 NGOTO=1,XGD=40000.,YGD=    0.,VCR=50.          ,CONS=4*100.          ,ACR=200.,
 LP=2,CUC=1.,22.,RVRB=40.,2.,
 NEL=500 ,XRAN= 5.,
 U=76.50,VGD=100.,
 RVRA=3600.             ,REMAX=3600.,AST=22.,VOLT=36.,
 UP=5,VMAX=.4,VMIT=-.03,COUV=8.854,
 VEL=-.03,.07,.21,.35,.66,
 PHO=-.123,-.035,.088,.211,.435,TORQ=-.05,.0,.05,.1,.6,
 PERC=.24,DPER=.24,ROLLR=13.57,
 OSMC=9.4,8.35,7.31,6.28,5.24,3.,GORQ=137.,181.,251.,347.,485.,1057.,
 IPP=5,AMPE=4.,6.6,8.4,10.8,13.6,21.0,COP=3.,SLOPE=-5.,
 VCOUL=2.,
 NDATA=1,
 $END
```

APPENDIX A

INPUT TO ROVER

The current input to ROVER is in NAMELIST format ($NAMI) for the UNIVAC 1108, EXEC 8. All references and figures refer to Reference 2 unless stated otherwise.

General Input

NDATA = 1 implies an output save device with the following binary records, one for each of the NINT integration intervals (NINT records for normal termination).

```
WRITE(1)TIM,(X(I),I=1,3),((B(I,J),I=1,3),J=1,3)
(U(I),I=1,6),(VDOT(I),I=1,6),((PNG(I,J),I=1,3),J=1,4),
(HINU(I,J),I=1,4),J=1,4)
```

where TIM is the time, X are the inertia coordinates of the vehicle origin, B is the direction cosine matrix, U are the six vehicle velocities ($u\ v\ w,\ \omega_x\ \omega_y\ \omega_z$) in body coordinates, VDOT are the six vehicle accelerations ($\dot{u}\ \dot{v}\ \dot{w} + \bar{\omega} \times \bar{U},\ \dot{\omega}_x\ \dot{\omega}_y\ \dot{\omega}_z$). The first three rows of HINU are the inertia coordinates of the four wheel hubs and the last row are the terrain elevations directly below the wheel hubs. PNG are the x,y,z body suspension forces of the four wheels.

TMEAN = time after which the following items are to be computed: fraction of time a wheel is off the ground, maximum wheel loads, and maximum acceleration.

X = single array of order 3 or the inertia X,Y,Z coordinates of the origin of the vehicle.

Z = double array of order 3x4 containing the body x,y,z coordinates of the wheel hubs (wheel and suspension fully extended).

RW = wheel radius.

PHI = initial ϕ angle in degrees (Figure 1).

THETA = initial θ angle in degrees (Figure 1).

PSI = initial ψ angle in degrees (Figure 1).

U = single array of order 6 containing initial rates $\{u\ v\ w\ \omega_x\ \omega_y\ \omega_z\}$.

NINT = number of time intervals (DELTIM) for integration.

DELTIM = time span of one time interval (maximum).

IPRT = printing integer (print every IPRT time interval).

NDOT = number of locations for additional acceleration output (not to exceed 20).

R = double array (3)(NDOT) of body x,y,z coordinates.

GM = moon's acceleration of gravity.

Weight Data

CM = constant to divide all weight data (mass conversion constant) CM = 0 implies CM = 1.

WM = weight of one unsprung wheel mass; in what follows do not include the unsprung wheel weight.

NMASS = 0 implies zero, first, and second weight moments will be supplied.

Y(1) = m (total sprung weight rather than sprung mass).

Y(2) = I_{xx}.

Y(3) = I_{yy}.

Y(4) = I_{zz}.

Y(5) = H_x.

Y(6) = H_y.

Y(7) = H_z.

Y(8) = I_{xy}.

Y(9) = I_{xz}.

Y(10) = I_{yz}.

NMASS = 1 implies detail weight breakdown.

NIT = number of masses, not to exceed 30.

$A(j,\alpha)$ = double array of order (NIT)(7) of weight data.

α = 1, weight.

α = 2, x coordinate.

α = 3, y coordinate.

α = 4, z coordinate.

α = 5, local x moment of inertia (about own cg).

α = 6, local y moment of inertia.

α = 7, local z moment of inertia DIMENSION A(30,7).

<u>Elevation Data</u>

NXY = 0, implies $CX\phi = 0$.

NXY = 1, implies $CX\phi$ may have a non-zero value.

CXA = X, location.

$CX\phi$ = slope parameter.

$A\phi$ = X-slope.

$B\phi$ = Y-slope.

$G\phi$ = constant amplitude.

$X\phi$ = origin for definition of X-slope.

$Y\phi$ = origin for definition of Y-slope.

NG = number of α-bumps/craters.

$XAL(\beta,\alpha)$ = double array of order 2xNG to locate α-bumps/crater,
β = 1 is X-coordinate (X_α),
β = 2 is Y-coordinate (Y_α).

NPØL = 1 implies polynomial of order NPOL - 1 of cornering friction coefficients vs. velocity ratio (AV2/AV1) will replace SF for all cases except when AV1 = 0. DIMENSION NPOL(6).

VRAT = array of order NPOL of velocity ratios.

CØR = array of order NPOL of cornering coefficients.

VMRAT = maximum velocity ratio. If VMRAT is exceeded, the velocity ratio will be set equal to VMRAT.

NRØL(f) = single array of order 4.
0 implies no rolling friction for wheel f.
1 implies rolling friction for wheel f.
If NSTER = 1, NROL(f) is automated into the applicable algorithm. If NBRAK(f) = 1 then NRØL(f) is assumed zero.

RF = coefficient of rolling friction.
RF = 0 implies no rolling friction.

VRØL = minimum velocity for full rolling friction.
If AV1 < VROL, then rf(equivalent) = RF x AV1/VROL.

NBRAK(f) = single array of order 4.
0 implies no braking for wheel f.
1 implies braking for wheel f.
If NGUID = 1 or NSTBR = 1, NBRAK(f) is automated into the applicable algorithm.

BF = coefficient of braking friction, zero implies braking is inoperative.

VBRAK = minimum velocity for full braking friction.
If AV1 < VBRAK, then bf(equivalent) = BF x AV1/VBRAK.

CØNS(f) = single array of order 4. Zero implies braking is inoperative for wheel f. The braking force is a minimum of CONS(f) and BF PNF(3,f) where PNF(3,f) is the normal ground force (along $\tau 3$).

NTØRQ(f) = single array of order 4.
0 implies no engine torque for wheel f.
1 implies engine torque for wheel f.

XHAL(β,α) = double array of order 2xNG for α-bump/crater diameters,
β = 1 is $X_{h\alpha}$,
β = 2 is $Y_{h\alpha}$.

HAL(α) = amplitudes (H_α).

NCF = number of center frequencies for random terrain, not to exceed 100.

CFR = single array of order NCF of center frequencies (cycles per amplitude).

AMC = single array of order NCF of power associated with center frequencies (amplitude squared).

WFREQ = X - washboard frequency in cycles per amplitude (sinusoidal).

WASHX = lag length associated with washboard frequency.

WAMP = amplitude of the washboard frequency.

NEL = number of points for print-out purposes only of random terrain contribution to elevation (Y = 0).

XRAN = X - distance interval along Y = 0 for printing out random terrain elevation. The starting point is X = 0, Y = 0.

REA = starting number to compute random phases for random terrain. If zero, REA will be internally computed.

Friction Force Data

Let AV1, AV2 be absolute value of wheel velocity along $\overline{\tau 1}$ and $\overline{\tau 2}$, respectively.

SF = coefficient of cornering friction (constant).

VSE = minimum velocity for full cornering friction. IF AV2 < VSE then sf(equivalent) = SF x AV2/VSE.

TF = coefficient of ground friction torque for wheel f. TF=0 implies no engine torque.

UNIT = $\pm$ 1.0, 1.0 implies forward motion, -1.0 implies rearward motion, and 0 implies no engine torque. If NSERMO = 1, then NTORQ(f) is tentatively set equal to 1 and the remaining velocity-torque data now described has a different meaning. See NSERMØ = 1.

NP = number of pieces of data (not to exceed 6) from which to construct a torque-velocity polynomial of order NP-1.

VEL = single array of velocities of order NP.

TØRQ = single array of torques of order NP.

VMAX = velocity limit above which torque = 0.

VMIN = velocity limit below which torque equals its polynomial value at VMIN.

<u>Suspension Characteristics (see Equation A13)</u>

N50 = 0 implies maximum input formation.

SL(α,f) = spring lengths for wheel f $\{\ell_{if}\ \ell_{jf}\ \ell_{kf}\}$.

SIA(α,f) = soft spring constants for wheel f $\{s_{iaf}\ s_{jaf}\ s_{kaf}\}$.

SIB(α,f) = hard spring constants for wheel f $\{s_{ibf}\ s_{jbf}\ s_{kbf}\}$.

DAMP(f) = damping constant suspension for f DIMENSION SL(3,4), SIA(3,4), SIB(3,4), CS(3,4), DAMP(4).

DAMC = power of velocity dependent damping force for suspension (zero implies linear damping, DAMC = 1).

CØLUMB = coulomb damping force for each suspension.

VCØUL = minimum vertical velocity to attain full calculated damping force, otherwise damping force = calculated force x $|V_{T_3}f|$/VCOUL.

DPER = fraction of tire-suspension velocity (along body z) associated with the tire. (1-DPER) is fraction of velocity associated with suspension damper.

CØLW = columb damping per tire.

CEW = damping constant for each tire.

DAMW = tire velocity exponent for damping force computation.

N50 = 1 implies minimum input formation.

S(f) = ℓ_{kf}.

SA(f) = s_{kaf}.

SB(f) = s_{kbf}.

One must also input the following: DAMP(f), DAMG, COLUMB, VCOUL, DPER, CØLW, CEW, DAMW.

N50 = 1 also implies the following:
$\ell_{if} = \ell_{jf} = 10\ell_{kf} = 10s(f)$,
$s_{iaf} = s_{jaf} = s_{ibf} = s_{jbf} = s_{kbf} = SB(f)$,
DIMENSION S(4), SA(4), SB(4), DAMP(4).

<u>Steering (see Figure A2)</u>

AF(f) = constant steering angle for wheel f in degrees.

N100 = 1 implies time dependent constant rate Ackerman steering (see Figure A2). Not applicable if NGUID = 1 or NSTBR = 1.
NSGAK = 0 implies double Ackerman.
NSGAK = 1 implies single Ackerman.

AG = initial steering angle in degrees for outside front wheel.

ST1 = steering rate in degrees/time for outside front wheel.

TIMA = initial time for onset of ST1.

TIMB = final time for ST1.

ST3 = steering rate in degrees/time for outside front wheel.

TIMC>TIMB = initial time for onset of ST3.

TIMD = final time for ST3; for N100=1 the steering angle, (AP), outside front wheel is given as follows:

AP1 = AG for t < TIMA,

AP2 = AG + ST1(t-TIMA) for TIMA < t < TIMB,

AP3 = AG + ST1(TIMA-TIMB) for TIMB < t < TIMC,

AP4 = AP3 + ST3(t-TIMC) for TIMC < t < TIMD,

AP5 = AP3 + ST3(TIMD-TIMC) for t > TIMD.

AST is a maximum outside wheel steering in degrees; AP1, ..., AP5 in absolute value will be limited by AST.

NSIN = 1 implies sinusoidal Ackerman steering. Not applicable if NGUID = 1, NSTBR = 1, N100 = 1.
NSGAK = 0 implies double Ackerman,
NSGAK = 1 implies single Ackerman.

AP = (AMP)SIN(ST1)(t-Tϕ) for front outside wheel for 0 < t < TSIN.

AMP = amplitude in degrees (positive real only let ST1 take on desired sign).

Tϕ = time lag.

TSIN = final time.

NTRIM = 1 implies elevation will be automated to trim the vehicle for 1 lunar g. The algorithm goes as follows. In body coordinates construct a vector from the vehicle origin to the ground at the intersection of the wheel centers. Call this vector {ALm}, and:

ALX = (Z(1,1) + Z(1,4))/2.

ALY = (Z(2,1) + Z(2,2))/2.

ALZ = -RW + Z(3,1) + DH,
where DH = (mass)(GM)B(3,3)/(4)SIA(3,1).

Of course this vector assumes elastic and geometry symmetry.

This new origin in inertia coordinates is computed as follows:

$$\begin{Bmatrix} X\phi \\ Y\phi \\ G\phi \end{Bmatrix} = \begin{Bmatrix} X(1) \\ X(2) \\ X(3) \end{Bmatrix} + [B] \begin{Bmatrix} ALX \\ ALY \\ ALZ \end{Bmatrix}$$

We must now compute slopes from a modified [B] matrix to account for the cg of the vehicle not coinciding with $X\phi$, $Y\phi$. Call this cg shift OFF1 and OFF2 corresponding to X and Y, respectively. This shift causes small angle changes THET1 and THET2, computed as follows:

$$THET1 = (DH)(OFF2)/(ALY-Z(2,1))^2,$$

$$THET2 = (-DH)(OFF1)/(ALX-Z(1,1))^2.$$

The [B] matrix can now be modified and a new direction cosine matrix [B1] computed. The desired slopes are now obtained as follows:

$$A\phi = -B1(1,3)/B1(3,3),$$

$$B\phi = -B1(2,3)/B1(3,3).$$

Ground vectors in terms of body vectors are given through the matrix $[BB] = [B1]^t[B]$. $v_{\tau 3} = 0$ implying $U(3) = -(BB(3,1)(U(1)) + BB(3,2)(U(2))/BB(3,3)$. If NCF and/or WFREQ > 0, then $G\phi$ and the direction cosine matrix will be modified to account for the random terrain and/or the washboard. If NCF > 0, then U(3) is set equal to zero.

Series Motor and Soil Data

NSERMϕ = 1 implies series motor and soil data.

MST(f) = array of order 4,
1 implies wheel f motor is operative,
0 implies wheel f motor is inoperative.

REMAX = maximum variable resistance.

RFIX = fix resistance.

VØLT = battery voltage.

CØNMEG = back emf constant.

DCØN = torque constant.

CMØT = current exponent for torque.

TFR = frictional torque.

TIN = moment of inertia of rotation for motor-wheel ports. If not given or zero. TIN = .5(WM) x RW^2. TIN will also be divided by CM.

CØP = minimum wheel omega (radians/time).

SLØPE = used in conjunction with CØP (see Figure 1, of this report).

VARI = value of initial variable resistance.

PERC = fraction of tire-suspension deformation associated with tire. Used to calculate torque and roll radius (if ROLLR = 0).

CØNV = conversion factor from mechanical to electrical power.

FAMP = increment of current for solution of non-linear equation (Equation 1 of this report). If zero, FAMP will be set equal to .1.

IPP = number of pieces of data (not to exceed 6) used to construct current-omega and torque-current polynomials (Equation 1 this report) for full throttle (REV = 0).

AMPE = single array of currents of order IPP.

ØGME = single array of angular wheel velocities of order IPP (radians/time).

GØRQ = single array of torques of order IPP. If TFR $\neq$ 0, then GØRQ must be modified.

NP = number of pieces of data (not to exceed 6) from which to construct a slip number-torque number polynomial (Equation 4 of this report) and a pull number-torque number polynomial (Equation 7 of this report).

VEL = single array of order NP of torque numbers.

TØRQ = single array of order NP of slip numbers.

PNØ = single array of order NP of pull numbers.

ROLLR = wheel roll radius. If zero, it will be set equal to instantaneous value of (RW - PERC x $\Delta\tau_f$) (see Figure A3 for $\Delta\tau_f$).

VMAX = maximum allowable torque number.

VMIT = minimum allowable torque number.

NREAR = 1 implies separate torque and pull numbers for rear wheels.

VRE = single array of order NP of torque numbers for rear wheels.

PRN = single array of order NP of pull numbers for rear wheels.

CURR = array of order four of current estimates.

Control System

NGUID = 1 implies control system.

XGD = X - inertia coordinate of destination.

YGD = Y - inertia coordinate of destination.

VCR = velocity tolerance limit.

ACR = acceleration tolerance limit. If either VCR or ACR is exceeded variable resistance of series motors, and/or braking of the wheels is affected.

VGD = preferred forward velocity of vehicle.

RVRA = resistance per time; rate of increase of variable resistance of series motor if VCR or ACR is exceeded.

LP = number of points to construct the rate RVRD (see Control Law) for the variable resistance.

CUC = single array of order LP of the operating currents.

RVRB = single array of order LP of rates.

Rev (variable resistance) = rev$^{\pm}$(RVRD)(time). The arrays CUC and RVRB are used to construct a polynomial of order LP-1 for rate (RVRD, see Control Law) vs. current. If in the process of decreasing the variable resistance (REV) the average current in the four motors remains below CUC(1) the variable resistance is set equal to 0. If in the process of changing the variable resistance the current exceeds CUC(LP) it will be set equal to CUC(LP). Therefore, CUC(LP) should be set equal to the maximum possible current (assuming REV and angular velocity vanish).

AST = maximum angle, in degrees, of outside front wheel for Ackerman steering law.

NSGAK = 0 implies double Ackerman.
1 implies single Ackerman.

PØWIN = overhead power consumption. Does not include motor-controller circuit; includes for instance, navigation system, displays, steering power requirements, etc.

NST(f) = array of order 4.
1 implies steering operative for wheel f.
0 implies steering angle set equal to zero at all times for wheel f.

ANH = minimum angle in degrees before onset of steering correction. If zero, ANH will be set to 1 degree.

Subject: A Digital Program for Stability and Performance Characteristics of a Four-Wheel Vehicle - Case 320

From: S. Kaufman

Distribution List

NASA Headquarters

A. S. Lyman/MAP
B. Milwitzky/MAE
J. F. Saunders, Jr./MAE
W. E. Stoney/MAE

MSC

R. H. Kohrs/PD7
C. T. Modlin/ES2
D. B. Pendley/PA
S. Ritchey/SM7
J. R. Sevier/PD4
D. C. Wade/ES2

MSFC

T. Bullock/S&E-ASTN-ADL
J. H. Furman/S&E-ASTN-AA
C. E. Green/S&E-ASTN-AD
W. B. Holland/S&E-ASTN-ADL
D. A. Kross/S&E-ASTN-ADL
S. F. Morea/PM-SAT-LRV
J. Nichols/S&E-ASTN-ADS
W. R. Perry/PM-ASTN-A
J. M. Sisson/PM-SAT-LRV
J. B. Sterett, Jr./S&E-ASTN-A

Bellcomm

G. M. Anderson
A. P. Boysen, Jr.
J. P. Downs*
D. R. Hagner
J. J. Hibbert
N. W. Hinners
W. W. Hough
J. A. Llewellyn
G. J. McPherson
J. Z. Menard
R. D. Raymond
J. D. Richey
I. M. Ross*
P. F. Sennewald
J. C. Slaybaugh
J. W. Timko*
R. L. Wagner
M. P. Wilson*
All Members of Department 2031
Central Files
Department 1024 File
Library

*Abstract Only