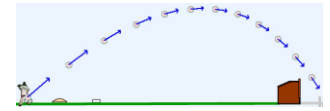


21.1.1 MG road-map: Projectile motion (2D)

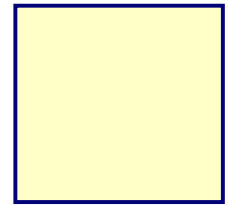
A baseball (particle Q) flies over Earth N (a Newtonian reference frame). Aerodynamic forces on the baseball are modeled as $-b\vec{v}$ (\vec{v} is Q 's velocity in N).

\hat{n}_x is horizontally-right, \hat{n}_y is vertically-upward, and N_o is home-plate (point fixed in N).



MG road-map for projectile motion x and y (\hat{n}_x, \hat{n}_y measures of Q 's position vector from N_o)

Variable	Translate/Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
x				Draw	Not applicable	$\square \cdot (\square = \square_{(20.1)})$
y				Draw	Not applicable	$\square \cdot (\square = \square_{(20.1)})$
x						MotionGenesis command ©
y						MotionGenesis command ©

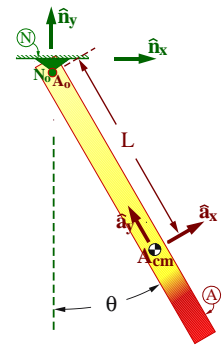


Draw FBD

Solution and simulation link at www.MotionGenesis.com ⇒ [Textbooks](#) ⇒ [Resources](#).

21.1.2 MG road-map: Rigid body pendulum (2D)

A non-uniform density rigid rod A is attached at point A_o of A by a frictionless revolute/pin joint to Earth N (Newtonian reference frame). The rod swings with a “pendulum angle” θ in a vertical plane that is perpendicular to unit vector \hat{a}_z .

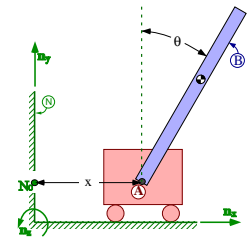


Variable	Translate/Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
θ				Draw		$\square \cdot (\square = \square_{(20.4)})$
θ						MotionGenesis command ©

Solution and simulation link at www.MotionGenesis.com ⇒ [Textbooks](#) ⇒ [Resources](#).

21.1.3 MG road-map: Inverted pendulum on cart (x and θ) (2D)

A rigid rod B is pinned to a massive cart A (modeled as a particle) that translates horizontally in a Newtonian reference frame N . The cart's position vector from a point N_o fixed in N is $x\hat{n}_x$ (\hat{n}_x is horizontally-right). B 's swinging motion in N is in a vertical plane perpendicular to \hat{n}_z (a unit vector fixed in both B and N).



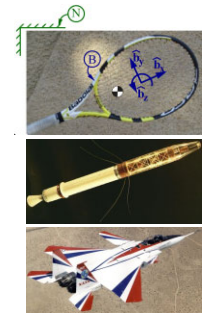
Variable	Translate/Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
x				Draw	Not applicable	$\square \cdot (\square = \square_{(20.1)})$
θ				Draw		$\square \cdot (\square = \square_{(20.4)})$
x						MotionGenesis command ©
θ						MotionGenesis command ©

Homework 15.8 and Chapter 25 complete these calculations.

21.1.4 MG road-map: Rotating rigid body (3D)

Shown right is a rotating rigid body B (e.g., tennis racquet, spacecraft, or aircraft) in a Newtonian reference frame N . Right-handed orthogonal unit vectors $\hat{b}_x, \hat{b}_y, \hat{b}_z$ are fixed in B .

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	<i>MG road-map equation</i>
ω_x	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/> · (<input type="text"/> = <input type="text"/>) (20.4)
ω_y	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/> · (<input type="text"/> = <input type="text"/>) (20.4)
ω_z	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/> · (<input type="text"/> = <input type="text"/>) (20.4)
ω_x	<input type="text"/>					MotionGenesis command ©
ω_y						MotionGenesis command ©
ω_z						MotionGenesis command ©

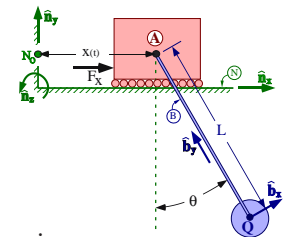


Solution and simulation link at www.MotionGenesis.com ⇒ [Textbooks](#) ⇒ [Resources](#).

Note: The “about point” is somewhat arbitrary. When B_{cm} is chosen: ${}^N \vec{H}^{B/B_{cm}} = \vec{I}^{B/B_{cm}} \cdot {}^N \vec{\omega}^B$. (15.2)

21.1.5 MG road-map: Bridge crane equations of motion (2D)

A payload (particle) Q is welded to a light rigid cable B which swings in a Newtonian frame N . Cable B is pinned to a massive trolley A that can move horizontally along a smooth slot fixed in N with a **specified** (known) displacement $x(t)$. A translational actuator with force measure F_x connects trolley A to point N_o of N .



MG road-map for pendulum angle θ , actuator force F_x , and cable tension

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	<i>MG road-map equation</i>
θ	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/>
F_x	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	Not applicable	<input type="text"/>
Tension	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	Not applicable	<input type="text"/>
θ	Dot(<input type="text"/> , System(<input type="text"/>).GetDynamics(<input type="text"/>))					MotionGenesis command ©
F_x	Dot(<input type="text"/> , System(<input type="text"/>).GetDynamics())					MotionGenesis command ©

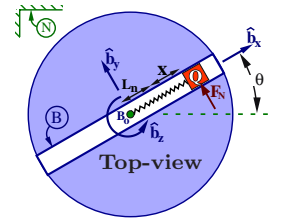
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Note: Only the θ road-map equation is needed to predict this system’s motion. The others are shown for illustrative purposes.

21.1.6 MG road-map: Particle on spinning slot (2D)

A particle Q slides on a straight slot B . The slot is connected with a revolute joint to a Newtonian frame N at point B_o so that B rotates in a horizontal plane perpendicular to $\hat{\mathbf{b}}_z$ ($\hat{\mathbf{b}}_z$ is vertically-upward and fixed in both B and N).

Note: Homework 14.7 completes the MG road-map calculations for x and θ .



MG road-map for x , θ , and F_N ($\hat{\mathbf{b}}_y$ measure of normal force on Q from B)

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
x	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	Not applicable	<input type="text"/> · (<input type="text"/> = <input type="text"/>)
θ	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	B_o	<input type="text"/> · (<input type="text"/> = <input type="text"/>)
F_N	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	Not applicable	<input type="text"/> · (<input type="text"/> = <input type="text"/>)
x	Dot(\mathbf{B}_x >, System(\mathbf{B}, Q).GetDynamics(\mathbf{B}_o))			MotionGenesis command ©		
θ	Dot(\mathbf{B}_z >, System(\mathbf{B}, Q).GetDynamics(\mathbf{B}_o))			MotionGenesis command ©		
F_N	Dot(\mathbf{B}_y >, System(\mathbf{B}, Q).GetDynamics(\mathbf{B}_o))			MotionGenesis command ©		

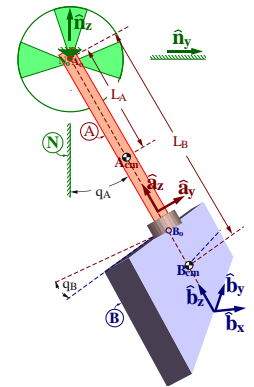
Note: The F_N road-map equation is needed to predict motion **if** a friction force depends on μF_N .

21.1.7 MG road-map: Motion of a chaotic double pendulum (3D)

Shown right is a mechanical model of a swinging babyboot (uniform plate B) attached by a shoelace (thin uniform rod A) to a fixed rigid support N . Rod A is attached to N by a revolute joint at point N_o of N . B is attached to A with a second revolute joint at point B_o so B can rotate freely about A 's axis.

Note: The revolute joints' axes are **perpendicular**, not parallel.

- The plate, rod, and support are rigid.
- The revolute joints are ideal (massless, frictionless, no slop/flexibility).
- Earth is a Newtonian reference frame N .
- Forces due to Earth's gravitation are uniform and constant.
- Other distance forces (electromagnetic and gravitational) and air-resistance are negligible.



Right-handed sets of unit vectors $\hat{\mathbf{n}}_x, \hat{\mathbf{n}}_y, \hat{\mathbf{n}}_z$; $\hat{\mathbf{a}}_x, \hat{\mathbf{a}}_y, \hat{\mathbf{a}}_z$; $\hat{\mathbf{b}}_x, \hat{\mathbf{b}}_y, \hat{\mathbf{b}}_z$ are fixed in N, A, B , respectively, with $\hat{\mathbf{n}}_x = \hat{\mathbf{a}}_x$ parallel to the revolute axis joining A to N , $\hat{\mathbf{n}}_z$ vertically-upward, $\hat{\mathbf{a}}_z = \hat{\mathbf{b}}_z$ parallel to the rod's long axis (and the revolute axis joining B to A), and $\hat{\mathbf{b}}_z$ perpendicular to plate B . q_A is the angle from $\hat{\mathbf{n}}_z$ to $\hat{\mathbf{a}}_z$ with $+\hat{\mathbf{n}}_x$ sense. q_B is the angle from $\hat{\mathbf{a}}_y$ to $\hat{\mathbf{b}}_y$ with $+\hat{\mathbf{a}}_z$ sense.

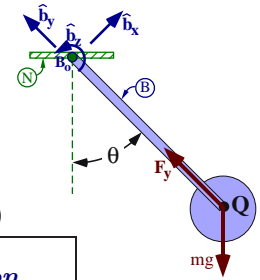
Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
q_A	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/> · (<input type="text"/> = <input type="text"/>)
q_B	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/> · (<input type="text"/> = <input type="text"/>)
q_A	Dot(<input type="text"/> , System(<input type="text"/>))			MotionGenesis command ©		
q_B	Dot(<input type="text"/> , <input type="text"/>))			MotionGenesis command ©		

Solution and simulation link at www.MotionGenesis.com ⇒ [Textbooks](#) ⇒ [Resources](#).

Note: The "about point" for the q_B road-map can be shifted from B_o to B_{cm} since $\hat{\mathbf{b}}_z \cdot \vec{\mathbf{M}}^{B/B_{cm}} = \hat{\mathbf{b}}_z \cdot \vec{\mathbf{M}}^{B/B_o}$. (17.4)

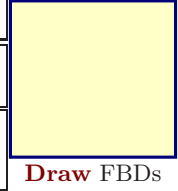
21.1.8 MG road-map: Particle pendulum (2D) – angle and tension

A particle Q is welded to the distal end of a light rigid rope B . The rope's other end attaches to a point B_o , fixed in a Newtonian reference frame N . The swinging motion of B and Q is in a vertical plane that is perpendicular to unit vector \hat{b}_z .



MG road-map for pendulum angle θ and tension F_y (\hat{b}_y measure of force on Q from B)

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
θ				Draw		$\square \cdot (\square = \square_{(20.4)})$
F_y				Draw	Not applicable	$\square \cdot (\square = \square_{(20.1)})$
θ F_y						MotionGenesis command © MotionGenesis command ©



Solution and simulation link at www.MotionGenesis.com ⇒ [Textbooks](#) ⇒ [Resources](#).

Note: Only the θ road-map equation is needed to predict motion. The other is shown for illustrative purposes.

21.1.9 MG road-map: Dynamicist on a turntable (ice-skater)

A dynamics instructor stands on a spinning turntable and swings a heavy dumb-bell Q inward and outward to change his spin-rate (similar to the ice-skater). Q is modeled as a particle rigidly attached (welded) to the end of the instructor's hands.

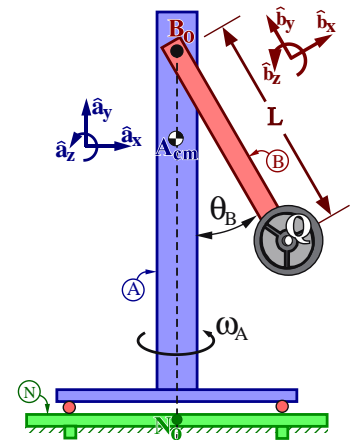
The schematic (below-right) shows a rigid body A (modeling the instructor's legs, torso, and head) that rotates (without friction) relative to Earth (a Newtonian reference frame N) about a vertical axis that is fixed in both A and N and which passes through both point N_o of N and point A_{cm} (A 's center of mass).



A massless rigid arm B (modeling the instructor's arms and hands) attaches to A by a revolute motor (shoulder/muscles) whose revolute axis is horizontal and located at point B_o of B (B_o lies on the vertical axis connecting N_o and A_{cm}).

The motor (muscles) **specifies** B 's angle θ_B relative to A to change in a known (prescribed) manner from 0 to π rad in 4 seconds ($\theta_B = \pi \frac{t}{4}$).

Right-handed orthogonal unit vectors $\hat{a}_x, \hat{a}_y, \hat{a}_z$ and $\hat{b}_x, \hat{b}_y, \hat{b}_z$ are fixed in A and B , respectively, with \hat{a}_y vertically-upward, $\hat{b}_z = \hat{a}_z$ parallel to the revolute motor's axis, and \hat{b}_y directed from Q to B_o .



Quantity	Symbol	Type	Value
Earth's gravitational constant	g	Constant	$9.8 \frac{m}{s^2}$
Distance between Q and B_o	L	Constant	0.7 m
Mass of Q	m	Constant	12 kg
A 's moment of inertia about line $\overline{A_{cm} B_o}$	I_{yy}	Constant	0.6 kg m^2
Angle from \hat{a}_y to \hat{b}_y with $+\hat{a}_z$ sense	θ_B	Specified	$0.25 \pi t$ rad
\hat{a}_y measure of A 's angular velocity in N	ω_A	Variable	

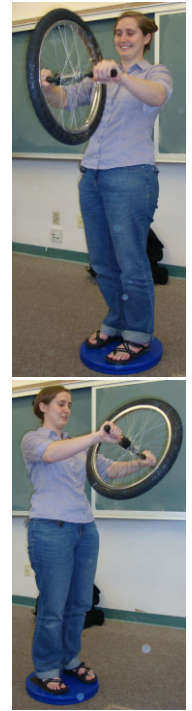
Complete the **MG road-map** for the turntable's "spin-rate" ω_A (Note: The "about point" is not unique)

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
ω_A				Draw		
ω_A	Dot(\square , System(\square)).GetDynamics(\square))					MotionGenesis command ©

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21.1.10 MG road-map: Instructor on turntable with spinning wheel (3D)

The pictures to the right shows dynamicist Dr. G standing on a spinning turntable and holding a spinning bicycle wheel.



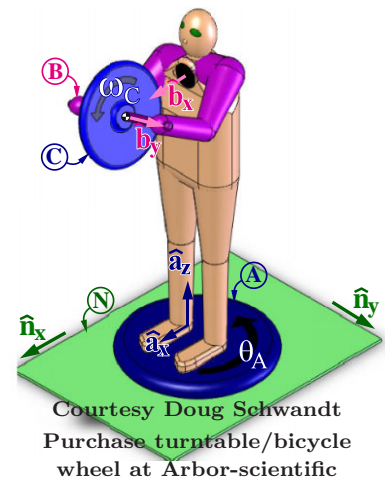
The mechanical model (below right) has a rigid body A (modeling the turntable, legs, torso, and head) that can freely rotate relative to Earth (Newtonian reference frame N) about a vertical axis that is fixed in both A and N and which passes through the center of the turntable (point N_o) and A_{cm} (A 's center of mass).

A light (massless) rigid frame B (modeling the shoulders, arms, hands, and a portion of the bicycle wheel's axle) is attached to A by a revolute motor at point B_o of B (B_o lies on the vertical axis passing through A_{cm}). The motor's revolute axis passes through points B_o and C_{cm} , is horizontal, and is parallel to $\hat{b}_x = \hat{a}_x$.

A rigid bicycle wheel C is attached to B by a frictionless revolute joint whose axis passes through C_{cm} (C 's center of mass) and is parallel to \hat{b}_y .

Right-handed orthogonal unit vectors $\hat{a}_x, \hat{a}_y, \hat{a}_z$ and $\hat{n}_x, \hat{n}_y, \hat{n}_z$ are fixed in A and N , respectively. Initially $\hat{a}_i = \hat{n}_i$ ($i = x, y, z$), and then rigid body A is subjected to a right-handed rotation characterized by $\theta_A \hat{a}_z$ where $\hat{a}_z = \hat{n}_z$ is directed vertically-upward and \hat{a}_x points from Dr. G's back to front (parallel to the axis of the revolute motor connecting A and B).

Unit vectors $\hat{b}_x, \hat{b}_y, \hat{b}_z$ are fixed in B . Initially $\hat{b}_i = \hat{a}_i$ ($i = x, y, z$), then B is subjected to a θ_B ($\hat{a}_x = \hat{b}_x$) right-handed rotation in A where \hat{b}_y is directed along the wheel's axle from Dr. G's right-to-left hand. Dr. G changes θ_B in a **specified** sinusoid manner with amplitude 30° and period 4 seconds.

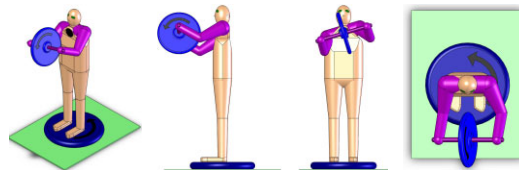


Quantity	Symbol and type		Value
Mass of C	m^C	Constant	2 kg
Distance between B_o and C_{cm}	L_x	Constant	0.5 m
A 's moment of inertia about B_o for \hat{a}_z	I_{zz}^A	Constant	0.64 kg m ²
C 's moment of inertia about C_{cm} for \hat{b}_x	I^C	Constant	0.12 kg m ²
C 's moment of inertia about C_{cm} for \hat{b}_y	J^C	Constant	0.24 kg m ²
Angle from \hat{n}_x to \hat{a}_x with $+\hat{n}_z$ sense	θ_A	Variable	
Angle from \hat{a}_y to \hat{b}_y with $+\hat{a}_x$ sense	θ_B	Specified	$\frac{\pi}{6} \sin(\frac{\pi}{2} t)$
\hat{b}_y measure of C 's angular velocity in B	ω_C	Variable	

Complete the **MG road-map** for θ_A and ω_C (the "about points" are not unique).

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation
θ_A	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/>
ω_C	<input type="text"/>	<input type="text"/>	<input type="text"/>	Draw	<input type="text"/>	<input type="text"/>
θ_A	Dot(<input type="text"/> , System(<input type="text"/> , <input type="text"/>).GetDynamics(<input type="text"/>))					MotionGenesis command ©
ω_C	Dot(<input type="text"/> , <input type="text"/>)					MotionGenesis command ©

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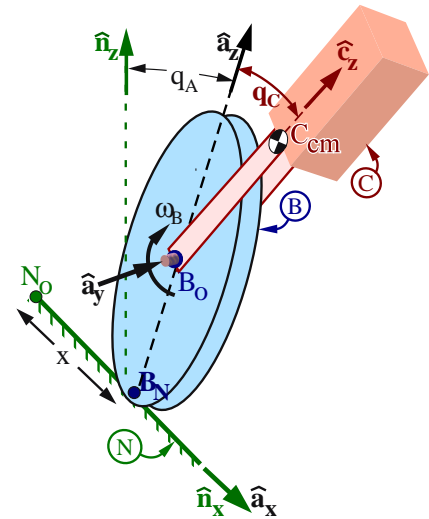
21.1.11 MG road-map: Bear riding a unicycle on a high-wire (3D)

The figures to the right show a (massless) pulley-wheel B that **rolls** along a taut (rigid) cable N (fixed on Earth, a Newtonian frame). Rigid body C (seat, rider, and balancing poles) attach to B with an ideal revolute motor at B_o (B 's centroid). The motor axis is aligned with B 's symmetry axis.

Right-handed orthogonal unit vectors $\hat{n}_x, \hat{n}_y, \hat{n}_z$ are fixed in N with \hat{n}_z vertically-upward and \hat{n}_x directed horizontally along the cable from a point N_o (fixed in N) to B_N (B 's rolling point of contact with N).

Right-handed orthogonal unit vectors $\hat{a}_x, \hat{a}_y, \hat{a}_z$ are directed with $\hat{a}_x = \hat{n}_x, \hat{a}_y$ parallel to the motor axis, and \hat{a}_z from B_N to B_o .

Right-handed unit vectors $\hat{c}_x, \hat{c}_y, \hat{c}_z$ are parallel to C 's principal inertia axes about C_{cm} (C 's center of mass), with $\hat{c}_y = \hat{a}_y$ and \hat{c}_z from B_o to C_{cm} (with balancing poles, C_{cm} is below B_o and L_C is negative).



Quantity	Symbol	Type	Value
Earth's gravitational constant	g	Constant	9.8 m/s ²
Radius of B	r_B	Constant	30 cm
\hat{c}_z measure of C_{cm} 's position vector from B_o	L_C	Constant	-35 cm
Mass of C	m^C	Constant	2 kg
C 's moment of inertia about C_{cm} for \hat{c}_x	I	Constant	3.4 kg m ²
C 's moment of inertia about C_{cm} for \hat{c}_y	J	Constant	3.2 kg m ²
C 's moment of inertia about C_{cm} for \hat{c}_z	K	Constant	2.8 kg m ²
\hat{a}_y measure of motor torque on B from C	T_y	Specified	below
Angle from \hat{n}_z to \hat{a}_z with $-\hat{n}_x$ sense	q_A	Variable	
\hat{a}_y measure of ${}^A\omega^B$ (${}^A\omega^B = \omega_B \hat{a}_y$)	ω_B	Variable	
Angle from \hat{a}_z to \hat{c}_z with $+\hat{a}_y$ sense	q_C	Variable	
\hat{n}_x measure of \mathbf{r}^{B_N/N_o}	x	Variable	

Form a complete set of **MG road-maps** for this systems's equations of motion (solution is not unique).
If necessary, add more **MG road-maps** so there are the same number of equations as unknowns.

Variable	Translate/ Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation	Additional Unknowns
q_A				Draw			
ω_B				Draw			
q_C				Draw			
x				Draw			
* Additional scalar constraint equation(s):							
MG road-map for ω_B is not unique. .							
q_A	Dot(System(MotionGenesis command ©
ω_B	Dot(System(MotionGenesis command ©
q_C	Dot(C.GetDynamics(MotionGenesis command ©
x	Dot(System(MotionGenesis command ©
SolveDt($\mathbf{x}' - \mathbf{r}*\omega_B = 0, \mathbf{x}'$)							MotionGenesis command ©

To move the unicycle to $x_{Desired} = 10$ m, use a "PD control law" with $T_y = -0.3(x - x_{Desired}) - 0.6\dot{x}$.

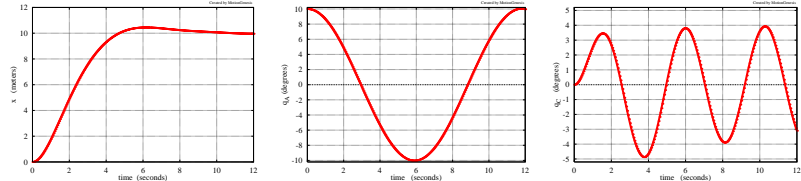
Optional simulation:

Plot x, q_A, q_C for $0 \leq t \leq 12$ sec.

Use initial values:

$$x = 0 \text{ m} \quad q_A = 10^\circ \quad \dot{q}_C = 0^\circ$$

$$\dot{x} = 0 \quad \dot{q}_A = 0 \quad \dot{q}_C = 0$$

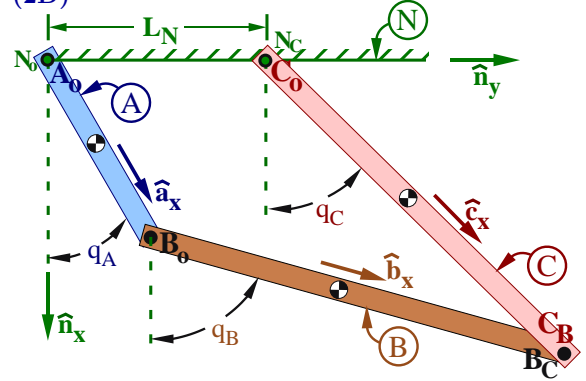


Solution at www.MotionGenesis.com ⇒ [Get Started](#) ⇒ Bear on rolling unicycle.

21.1.12 MG road-map: Four-bar linkage statics (2D)

The figure to the right shows a planar four-bar linkage consisting of frictionless-pin-connected uniform rigid links A, B, and C and ground N.

- Link A connects to N and B at points A_o and A_B
- Link B connects to A and C at points B_o and B_C
- Link C connects to N and B at points C_o and C_B
- Point N_o of N is coincident with A_o
- Point N_C of N is coincident with C_o



Right-handed orthogonal unit vectors $\hat{a}_i, \hat{b}_i, \hat{c}_i, \hat{n}_i$ ($i = x, y, z$) are fixed in A, B, C, N, with:

- \hat{a}_x directed from A_o to A_B
- \hat{b}_x directed from B_o to B_C
- \hat{c}_x directed from C_o to C_B
- \hat{n}_x vertically-downward
- \hat{n}_y directed from N_o to N_C
- $\hat{a}_z = \hat{b}_z = \hat{c}_z = \hat{n}_z$ parallel to pin axes

As in Hw 8.7, create the following “**loop equation**” and dot-product with \hat{n}_x and \hat{n}_y .

$$L_A \hat{a}_x + L_B \hat{b}_x - L_C \hat{c}_x - L_N \hat{n}_y = \vec{0}$$

Quantity	Symbol	Value
Length of link A	L_A	1 m
Length of link B	L_B	2 m
Length of link C	L_C	2 m
Distance between N_o and N_C	L_N	1 m
Mass of A	m^A	10 kg
Mass of B	m^B	20 kg
Mass of C	m^C	20 kg
Earth’s gravitational acceleration	g	$9.81 \frac{m}{s^2}$
\hat{n}_y measure of force applied to C_B	H	200 N
Angle from \hat{n}_x to \hat{a}_x with $+\hat{n}_z$ sense	q_A	Variable
Angle from \hat{n}_x to \hat{b}_x with $+\hat{n}_z$ sense	q_B	Variable
Angle from \hat{n}_x to \hat{c}_x with $+\hat{n}_z$ sense	q_C	Variable

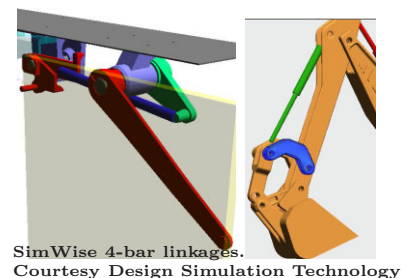
Complete the following **MG road-map** to determine this systems’s **static configuration**.

Variable	Translate/Rotate	Direction (unit vector)	System S	FBD of S	About point	MG road-map equation	Additional Unknowns	
				Draw			F_x^C, F_y^C	
				Draw			F_x^C, F_y^C	
				Draw			F_x^C, F_y^C	
* Additional scalar constraint equation:				$-L_A \sin(q_A) \dot{q}_A - L_B \sin(q_B) \dot{q}_B + L_C \sin(q_C) \dot{q}_C = 0$				
* Additional scalar constraint equation:				$L_A \cos(q_A) \dot{q}_A + L_B \cos(q_B) \dot{q}_B - L_C \cos(q_C) \dot{q}_C = 0$				
q_A	Dot(System().GetStatics(MotionGenesis command ©
q_B	Dot().GetStatics(MotionGenesis command ©
q_C	Dot(C.GetStatics(MotionGenesis command ©

Determine the **static equilibrium** values of q_A, q_B, q_C . Use your intuition (guess), circle the **stable** solution.

Solution 1	$q_A \approx 20.0^\circ$	$q_B \approx 71.7^\circ$	$q_C = 38.3^\circ$
Solution 2	$q_A \approx 249.3^\circ$	$q_B \approx 140.2^\circ$	$q_C = 199.1^\circ$
Solution 3	$q_A \approx 30.7^\circ$	$q_B \approx 226.1^\circ$	$q_C = 254.7^\circ$

Solution at www.MotionGenesis.com ⇒ [Get Started](#) ⇒ Four-bar linkage



SimWise 4-bar linkages. Courtesy Design Simulation Technology