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The Dirichlet-Neumann Schwarz alternating method for contact problems in elastodynamics




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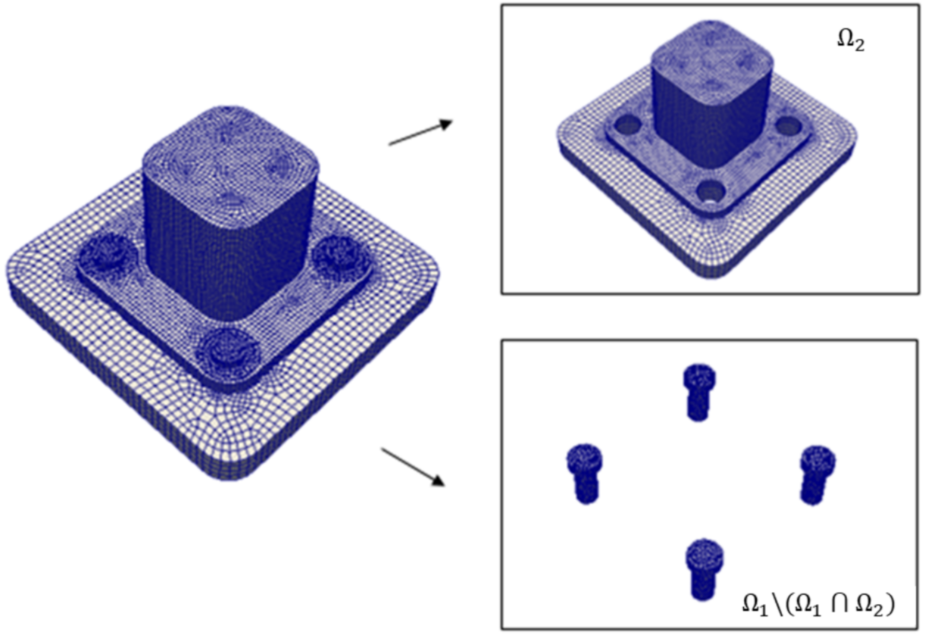
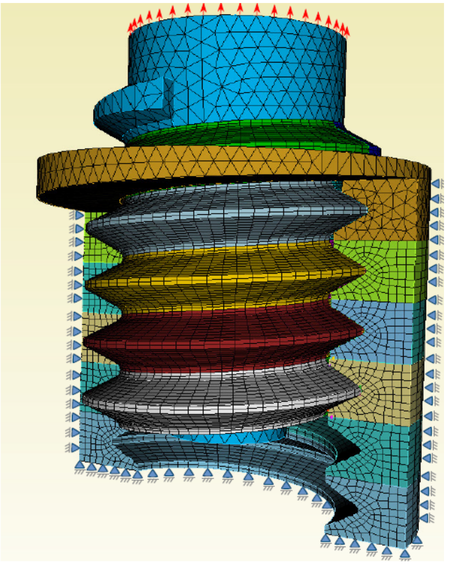
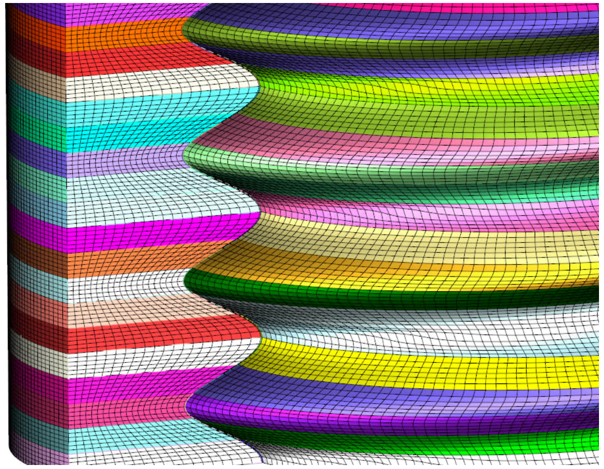
Numerical simulation of challenging mechanical contact problems

Localized contact, impact, touching surfaces, sliding, bolted/fastener joint, …
→ presence of nonlinearities and lack of smoothness







→ Need a robust, stable and accurate method for mechanical contact

- **accurate prediction** of quantities of interest (velocities, contact forces, energies, …)
- **multiscale & multiphysics** context (different time integrators, solvers, meshes, material models for different bodies)
- numerical **efficiency** and **robustness**
- **non-intrusive implementation** in existent legacy solvers (e.g. Sierra/Solid Mechanics (Sierra/SM), Albany, …)

Numerical simulation of challenging multiscale contact problems

Conventional contact methods

- introduce **contact constraints** into the variational form
- solve all bodies involved in contact as a **"coupled" system**

Penalty method – amount of interpenetration ~ contact pressure
[G. L. Goudreau et al. (1982) | T. Belytschko et al. (1991)]
Lagrange Multipliers method – additional Lagrange constraints
[T. J. R. Hughes. (1976) | K. J. Bathe et al. (1956)]
Perturbed and **Augmented Lagrangian methods** – constrained optimization theory, hybrid penalty/LM approach
[J. C. Simo et al. (1985, 1992) | R. Glowinski et al. (1989)]
Nitsche method – optimization problem with contact constraints
[F. Chouly et al. (2016) | P. Wriggers et al. (2008)]

\+ well-established (proven convergence, ...)
– accuracy and stability often affected by problem-dependent parameters
– all bodies are coupled and solved simultaneously
– intrusive implementation

Schwarz alternating method

- **treats each body separately** (as non-overlapping subdomains)
- prevents interpenetration through an **alternating Dirichlet-Neumann iterative process**

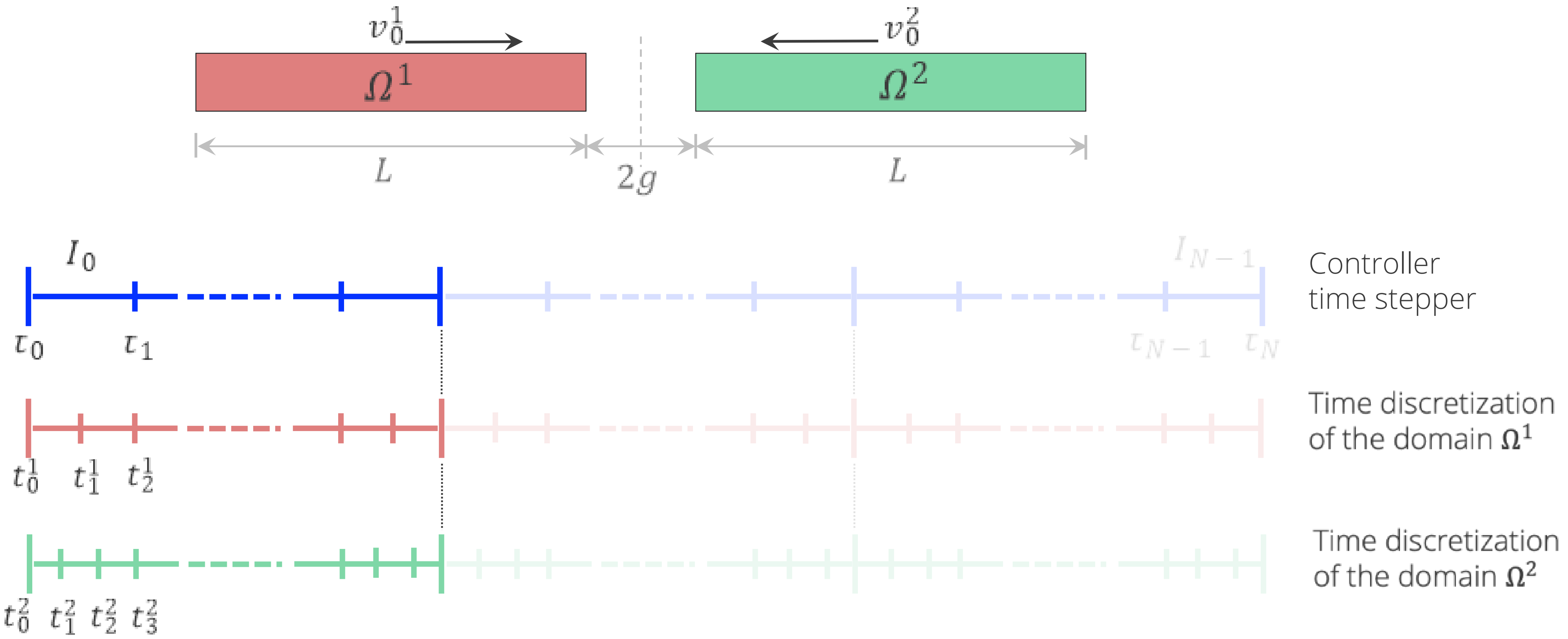
Domain Decomposition context – solving PDEs on irregular domains by splitting them into domains of regular shape, overlapping and non-overlapping approaches *[H. Schwarz (1870) | P. I. Lions (1990)]*
Multiscale coupling – overlapping approach *[A. Mota et al. (2017, 2021)]*
Contact/impact dynamics – non-overlapping approach *[A. Mota et al. (2023)*]*

\+ strong theoretical basis (domain decomposition context)
\+ flexible (different time integration schemes, solvers, meshes, material models for different bodies)
\+ non-intrusive implementation
– iterative process and transfer operators

Schwarz alternating method for contact problems

Before the contact phase:

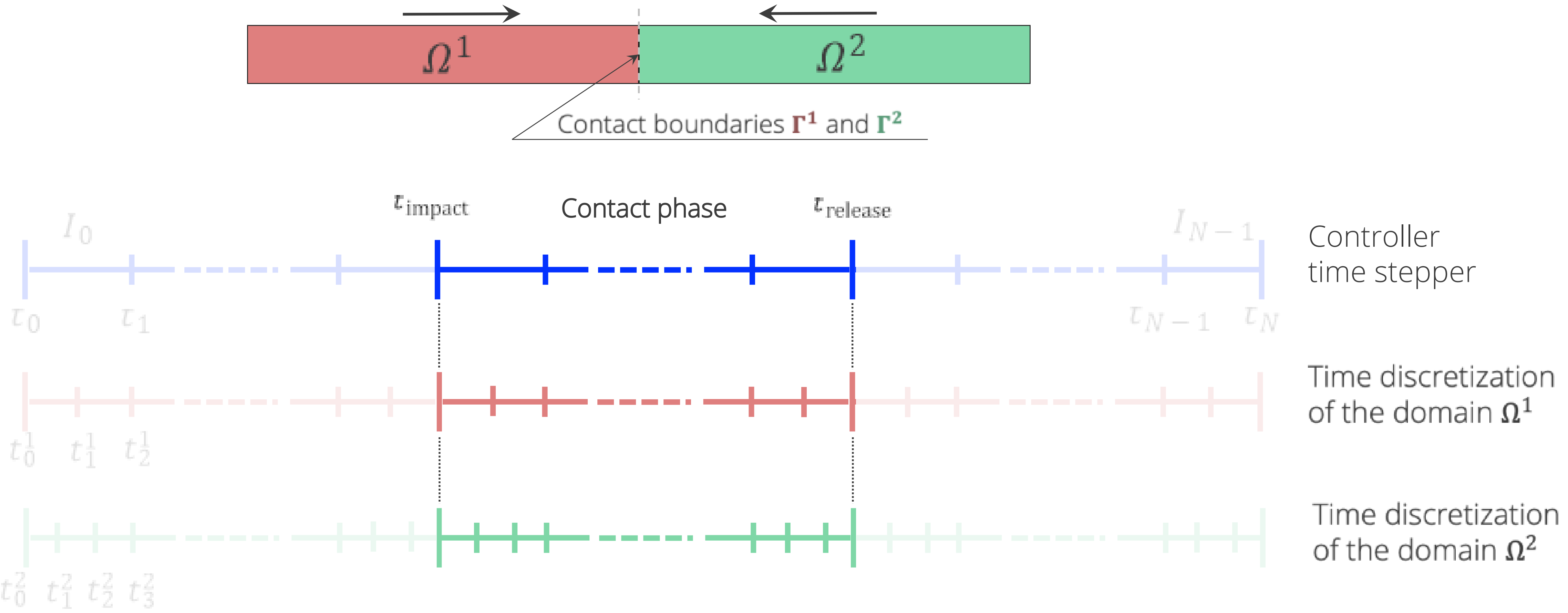
- solve PDEs in each body separately (different solvers, discretization techniques, time integrators, ...)
- check contact criteria at each controller time step (overlap/distance conditions, compression condition, ...)



Schwarz alternating method for contact problems

During the contact phase:

- **solve PDEs in each body separately** (different solvers, discretization techniques, time integrators, ...)
- prevent interpenetration through an iterative process based on the **Dirichlet-Neumann contact boundary conditions**
- **check contact criteria** at each controller time step (overlap/distance conditions, compression condition, ...)



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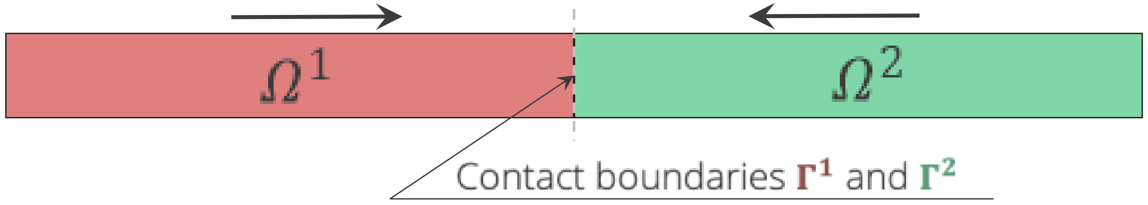
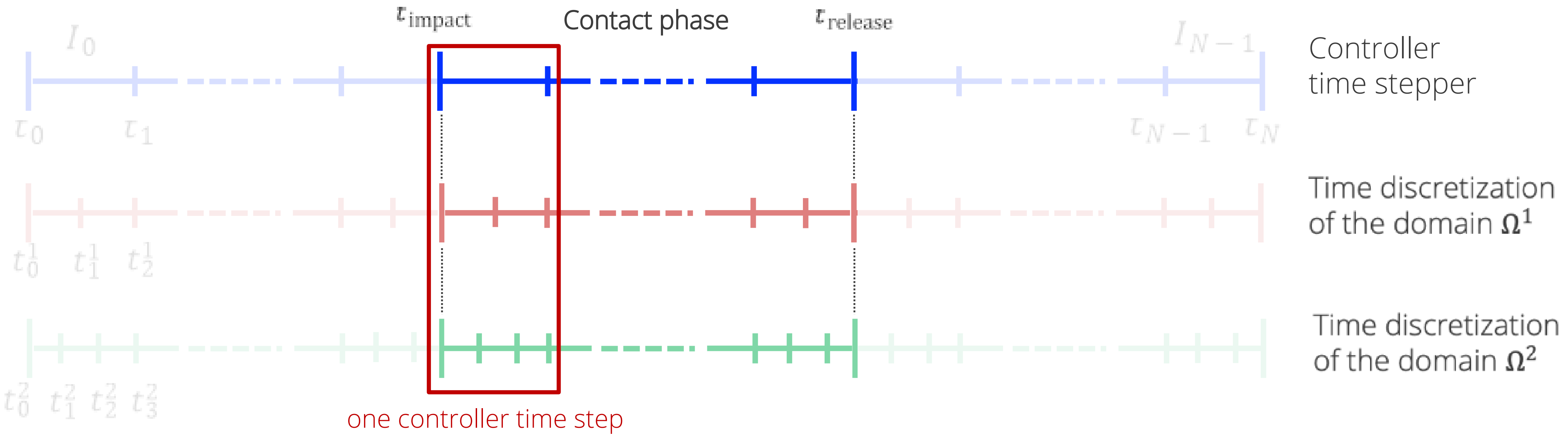
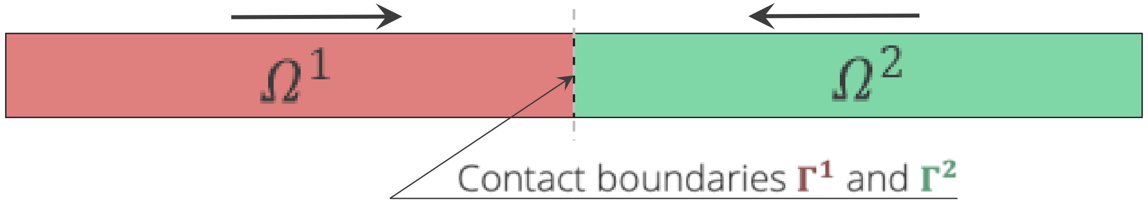
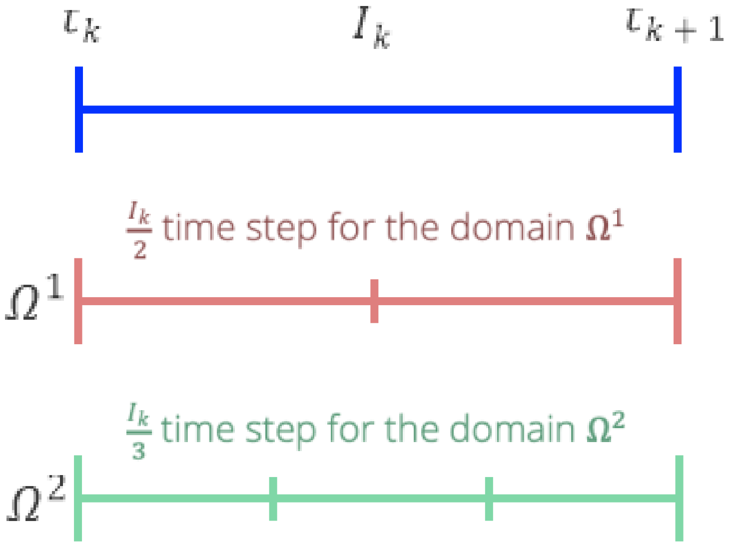




Schwarz alternating method for contact problems





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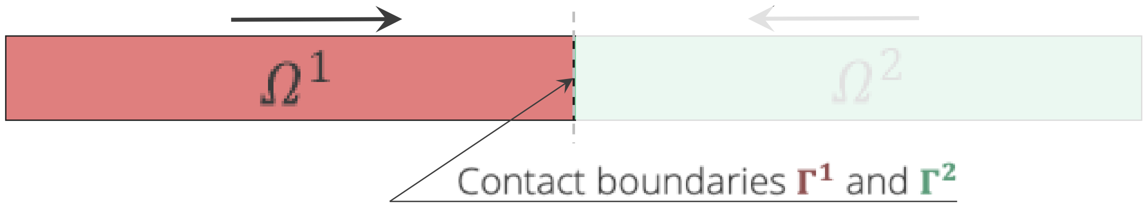
Iterate until Schwarz convergence criteria are satisfied

Schwarz alternating method for contact problems



Notations

displacement	$\boldsymbol{\varphi}$	mass density	ρ
acceleration	$\ddot{\boldsymbol{\varphi}}$	body force	$\rho \boldsymbol{B}$
Piola-Kirchoff stress	$\boldsymbol{P}$	traction	$\boldsymbol{T}$

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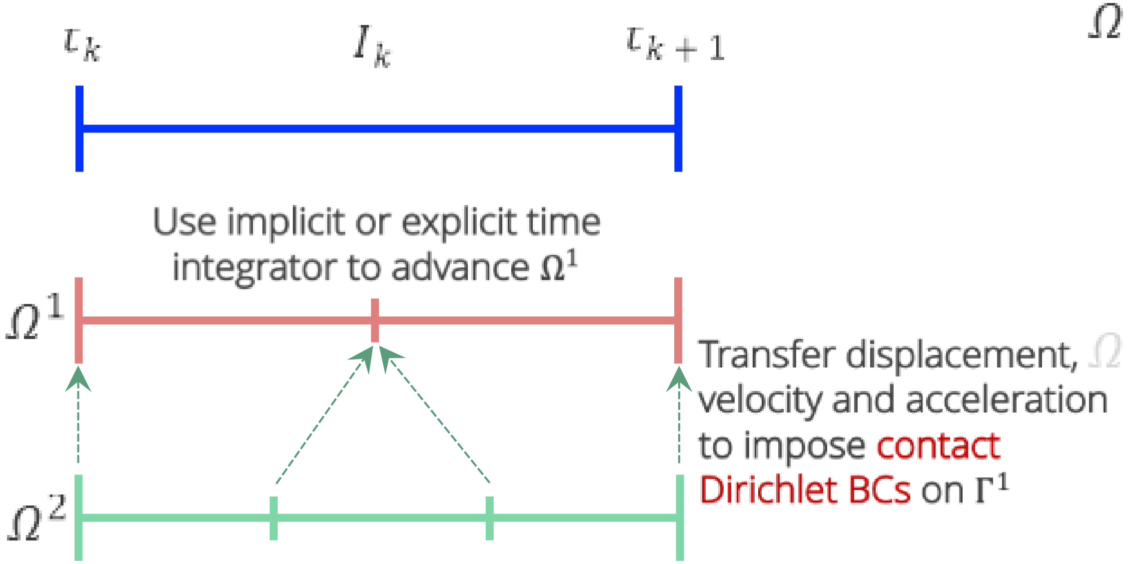
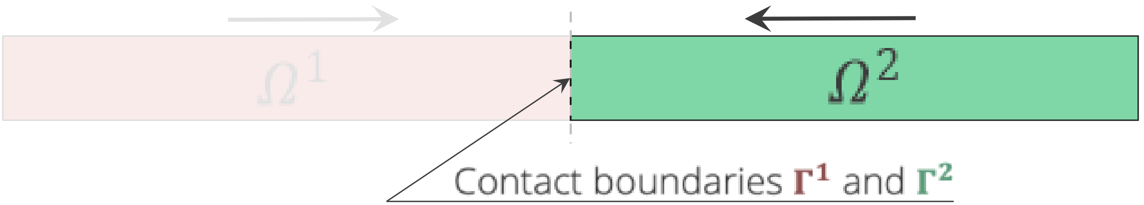


Iterate until Schwarz convergence criteria are satisfied

Schwarz alternating method for contact problems



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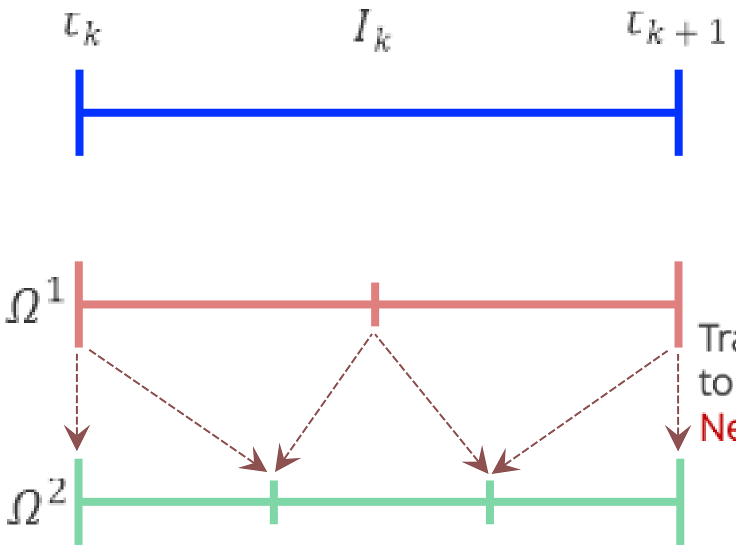

Transfer traction to impose contact Neumann BCs on Γ^2

Use implicit or explicit time integrator to advance Ω^2

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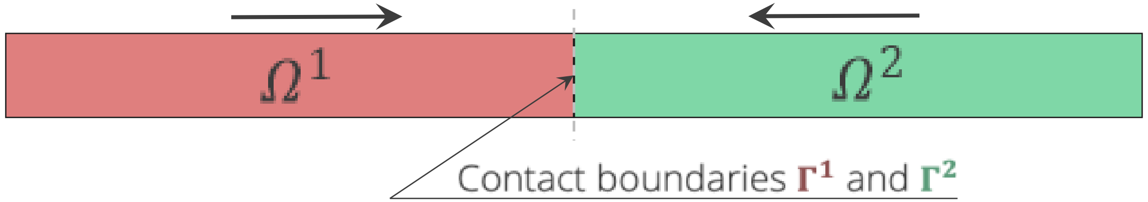
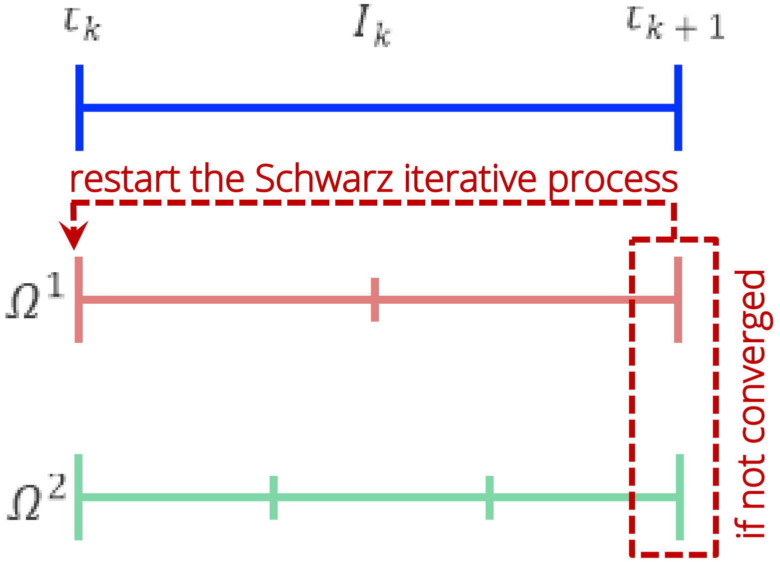
Schwarz alternating method for contact problems





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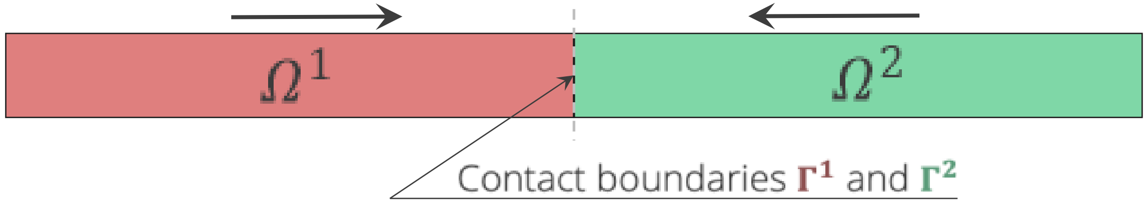

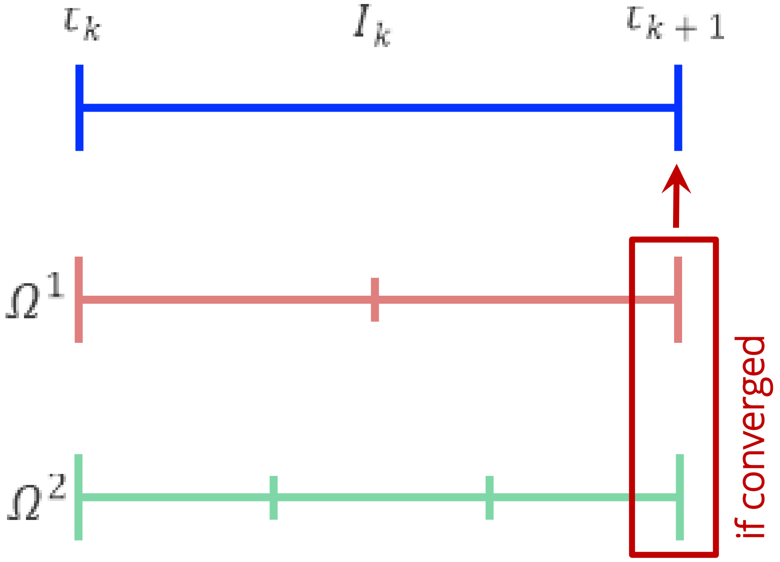

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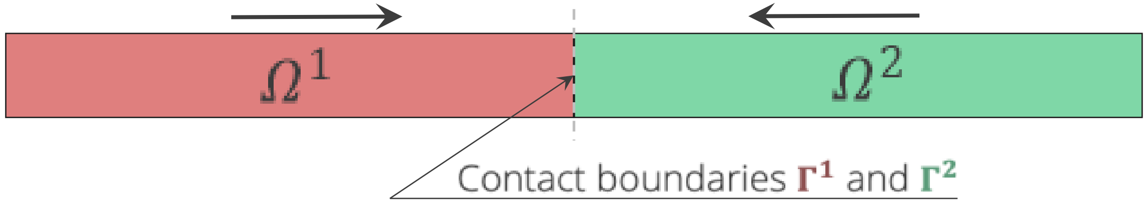
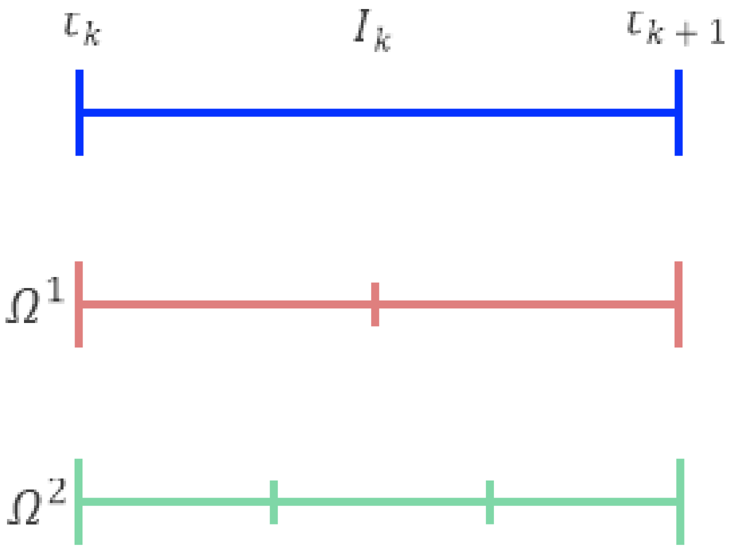
Schwarz alternating method for contact problems





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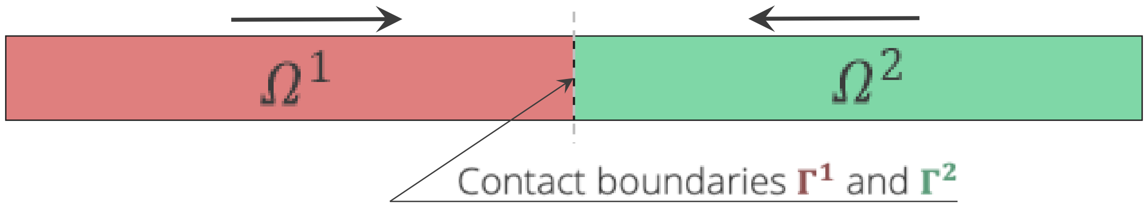
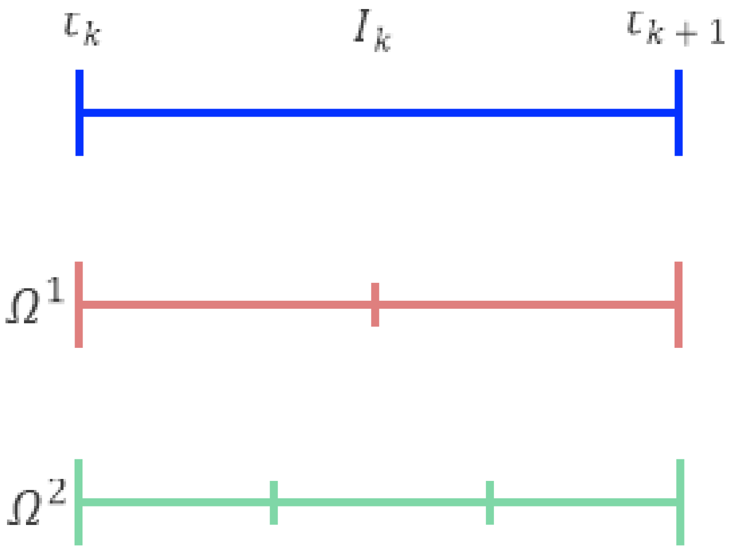
- Can be easily coupled with different time integrators – implicit, explicit Newmark-β, … schemes

Schwarz alternating method for contact problems





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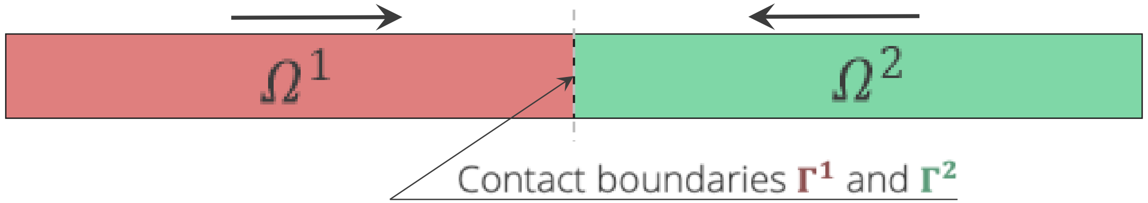
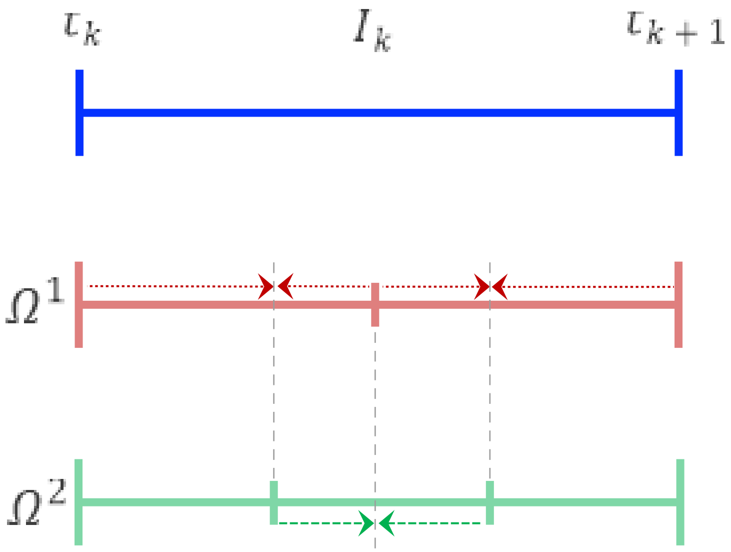
- Can be easily coupled with different time integrators – implicit, explicit Newmark-β, … schemes
- Challenge: appropriate transfer operators for displacement and traction

Schwarz alternating method for contact problems





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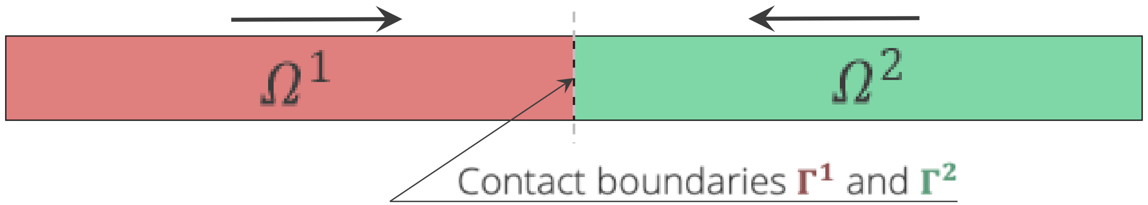
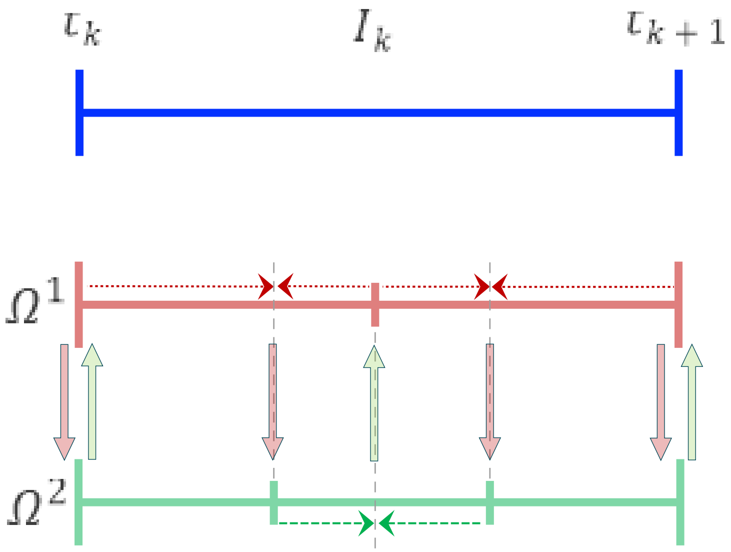
- Information transfer in time (interpolation)

Schwarz alternating method for contact problems





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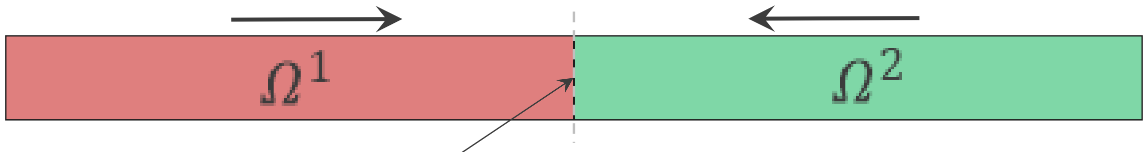
$$\Omega^2 \begin{cases} \operatorname{div} \boldsymbol{P}^n + \rho \boldsymbol{B} = \rho \ddot{\boldsymbol{\varphi}}^n & \text{in } \Omega^2 \times I_k & \text{Dynamic problem} \\ \boldsymbol{\varphi}^n(\boldsymbol{x}, t) = \boldsymbol{\chi} & \text{on } \partial_{\boldsymbol{\varphi}} \Omega^2 \times I_k & \text{Regular Dirichlet BCs} \\ \boldsymbol{P}^n \boldsymbol{N} = \boldsymbol{T} & \text{on } \partial_{\boldsymbol{T}} \Omega^2 \times I_k & \text{Regular Neumann BCs} \\ \boldsymbol{P}^n \boldsymbol{N} = \boxed{\mathcal{P}^{\boldsymbol{T}}_{(\Gamma^1 \to \Gamma^2) \times I_k} \boldsymbol{T}^n(\Omega^1, t)} & \text{on } \Gamma^2 \times I_k & \text{Contact Neumann BCs} \end{cases}$$

- Information transfer in time (interpolation)
- Information transfer in space (transfer operators)

Schwarz alternating method for contact problems



Contact boundaries $\boldsymbol{\Gamma}^{\text{src}}$ and $\boldsymbol{\Gamma}^{\text{dst}}$

- Displacement transfer operator from $\boldsymbol{\Gamma}^{\text{src}}$ to $\boldsymbol{\Gamma}^{\text{dst}}$

$$\mathcal{P}^{\varphi} = \left[\int_{\Gamma^{\text{dst}}} \mathcal{N}^{\text{dst}} \left(\mathcal{N}^{\text{dst}}\right)^{\text{T}} \, \mathrm{d}S \right]^{-1} \left[\int_{\Gamma^{\text{dst}}} \mathcal{N}^{\text{dst}} \left(\mathcal{N}^{\text{src}}\right)^{\text{T}} \, \mathrm{d}S \right]$$

- Traction transfer operator from $\boldsymbol{\Gamma}^{\text{src}}$ to $\boldsymbol{\Gamma}^{\text{dst}}$

$$\mathcal{P}^{T} = \left[\int_{\Gamma^{\text{dst}}} \mathcal{N}^{\text{dst}} \left(\mathcal{N}^{\text{src}}\right)^{\text{T}} \, \mathrm{d}S \right] \left[\int_{\Gamma^{\text{src}}} \mathcal{N}^{\text{src}} \left(\mathcal{N}^{\text{src}}\right)^{\text{T}} \, \mathrm{d}S \right]^{-1}$$

$\mathcal{N}^{\text{src}}$ and $\mathcal{N}^{\text{dst}}$ - finite elements interpolation functions defined on $\boldsymbol{\Gamma}^{\text{src}}$ and $\boldsymbol{\Gamma}^{\text{dst}}$

$$\Omega^1 \begin{cases} \operatorname{div} \boldsymbol{P}^n + \rho \boldsymbol{B} = \rho \ddot{\boldsymbol{\varphi}}^n & \text{in } \Omega^1 \times I_k & \text{Dynamic problem} \\ \boldsymbol{\varphi}^n(\boldsymbol{x}, t) = \boldsymbol{\chi} & \text{on } \partial_{\boldsymbol{\varphi}} \Omega^1 \times I_k & \text{Regular Dirichlet BCs} \\ \boldsymbol{P}^n \boldsymbol{N} = \boldsymbol{T} & \text{on } \partial_{\boldsymbol{T}} \Omega^1 \times I_k & \text{Regular Neumann BCs} \\ \boldsymbol{\varphi}^n(\boldsymbol{x}, t) = \boxed{\mathcal{P}^{\varphi}_{(\Gamma^2 \to \Gamma^1) \times I_k} \boldsymbol{\varphi}^{n-1}(\Omega^2, t)} & \text{on } \Gamma^1 \times I_k & \text{Contact Dirichlet BCs} \end{cases}$$

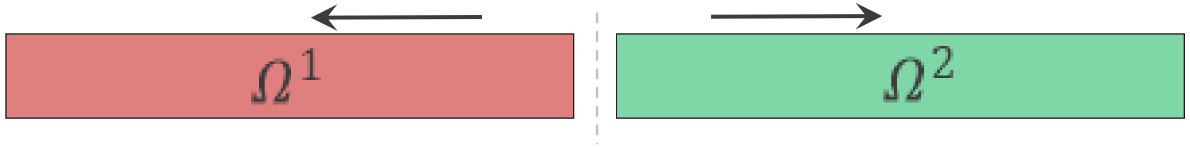
$$\Omega^2 \begin{cases} \operatorname{div} \boldsymbol{P}^n + \rho \boldsymbol{B} = \rho \ddot{\boldsymbol{\varphi}}^n & \text{in } \Omega^2 \times I_k & \text{Dynamic problem} \\ \boldsymbol{\varphi}^n(\boldsymbol{x}, t) = \boldsymbol{\chi} & \text{on } \partial_{\boldsymbol{\varphi}} \Omega^2 \times I_k & \text{Regular Dirichlet BCs} \\ \boldsymbol{P}^n \boldsymbol{N} = \boldsymbol{T} & \text{on } \partial_{\boldsymbol{T}} \Omega^2 \times I_k & \text{Regular Neumann BCs} \\ \boldsymbol{P}^n \boldsymbol{N} = \boxed{\mathcal{P}^{T}_{(\Gamma^1 \to \Gamma^2) \times I_k} \boldsymbol{T}^n(\Omega^1, t)} & \text{on } \Gamma^2 \times I_k & \text{Contact Neumann BCs} \end{cases}$$

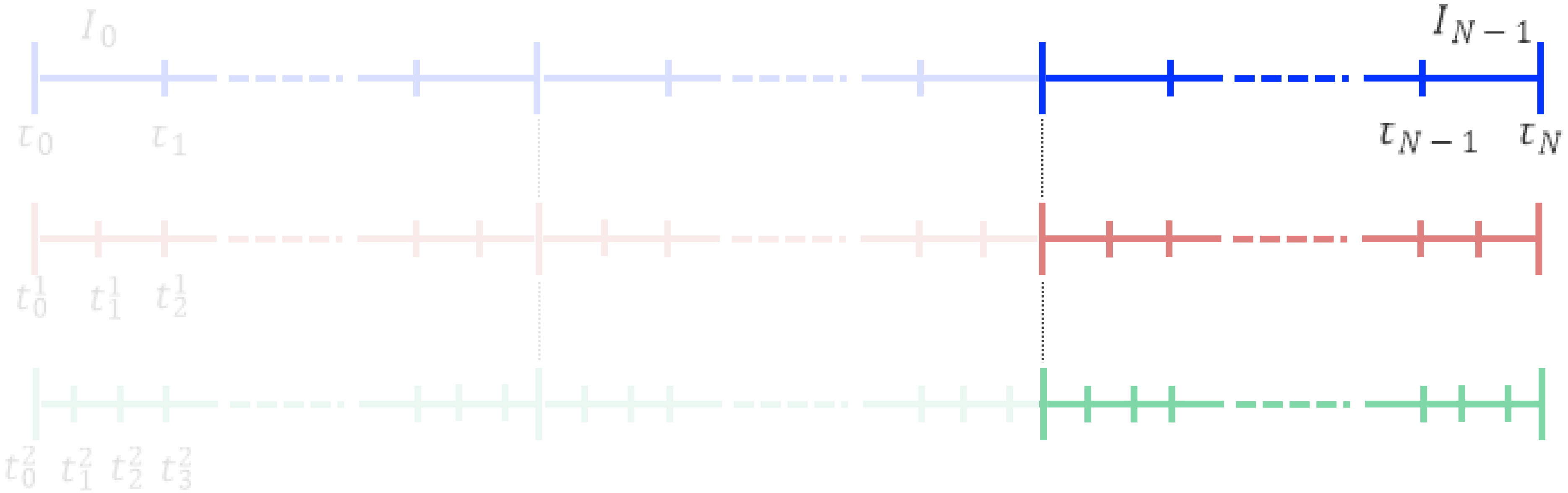
- Generic (appropriate for different geometries, mesh types, element sizes, ...)
- Same operator used for all Schwarz iterations within one controller time step

Schwarz alternating method for contact problems

After the contact phase:

- **solve PDEs in each body separately** (different solvers, discretization techniques, time integrators, ...)
- **check contact criteria** at each controller time step (overlap/distance conditions, compression condition, ...)



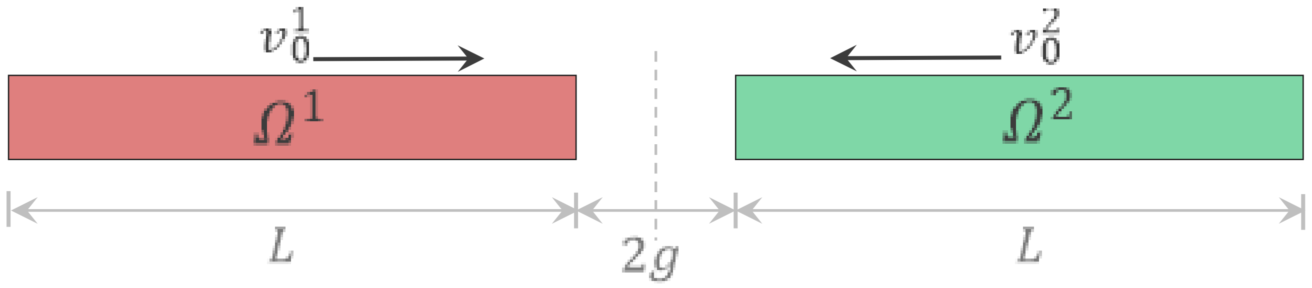


Controller time stepper

Time discretization of the domain Ω^1

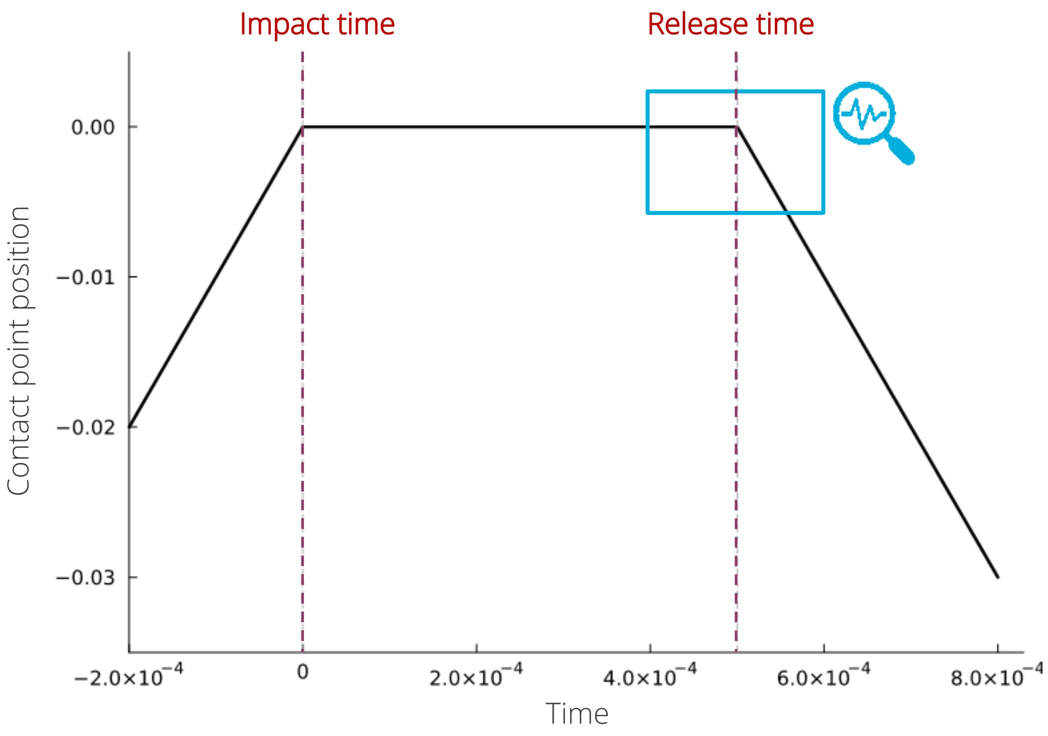
Time discretization of the domain Ω^2

Impact of two 1D linear elastic prismatic rods



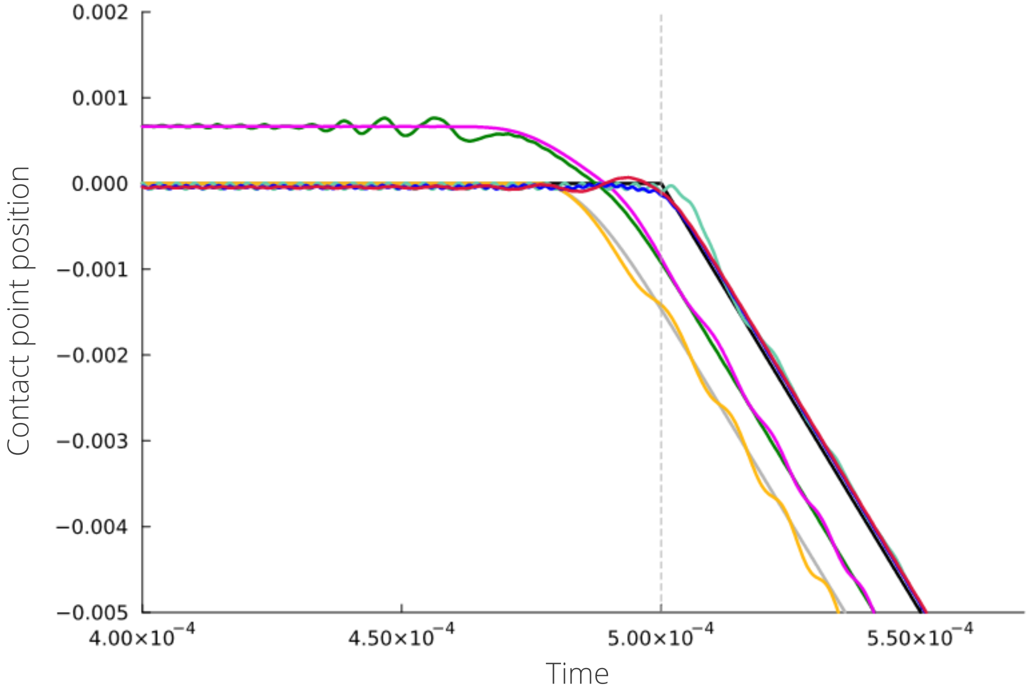
- **Analytical solution** available in *[Carpenter et al., 1991]*
- **Newmark-β** time integrator
- **Numerical comparison**: Schwarz method vs conventional contact methods
  - implicit and explicit Lagrange multiplier methods
  - implicit and explicit penalty methods
  - explicit-explicit, implicit-implicit, implicit-explicit Schwarz methods

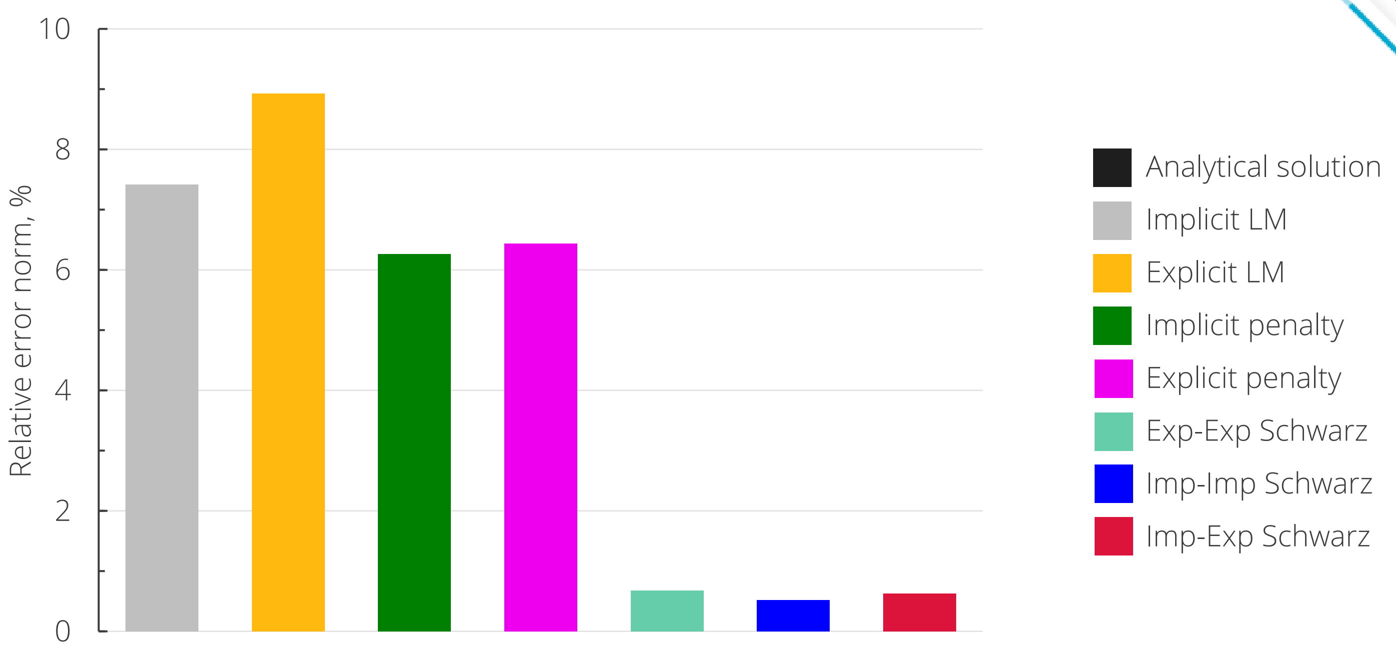
Contact point position



Analytical solution

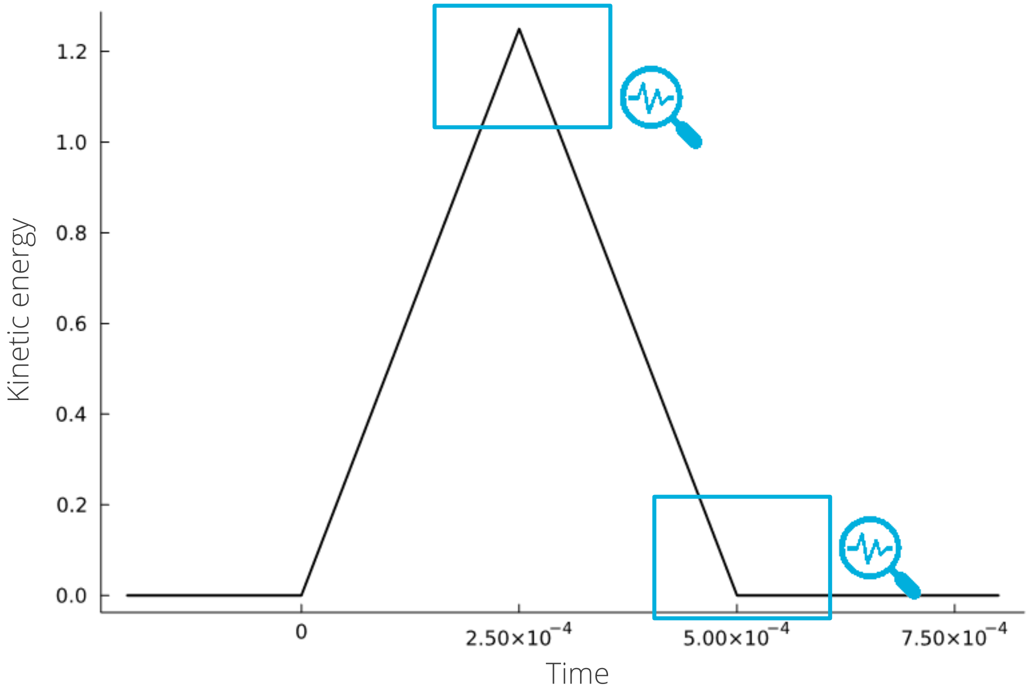
Contact point position





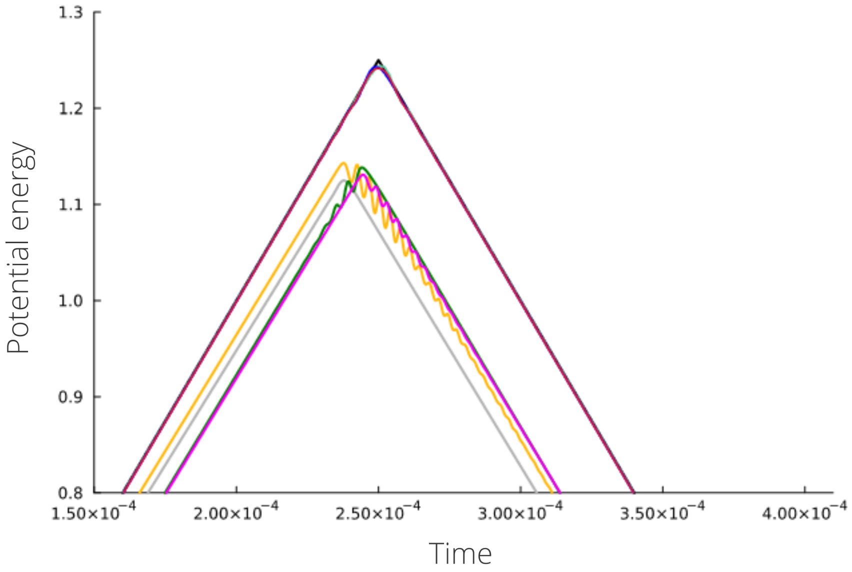
- **Lagrange Multiplier methods:** under-predict the release time
- **Penalty methods**: over-predict the contact point position and under-predict the release time
- **Schwarz methods**: accurately predict the contact point position and release time

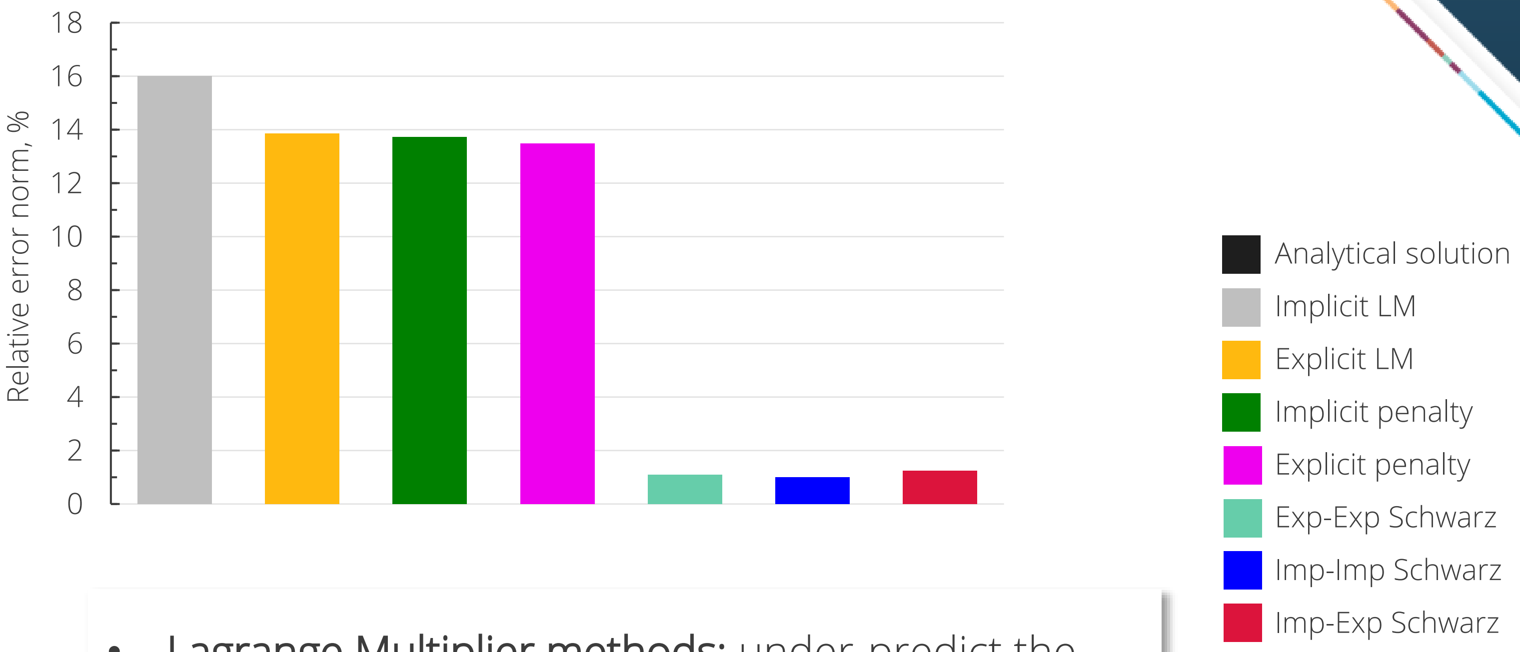
Potential energy

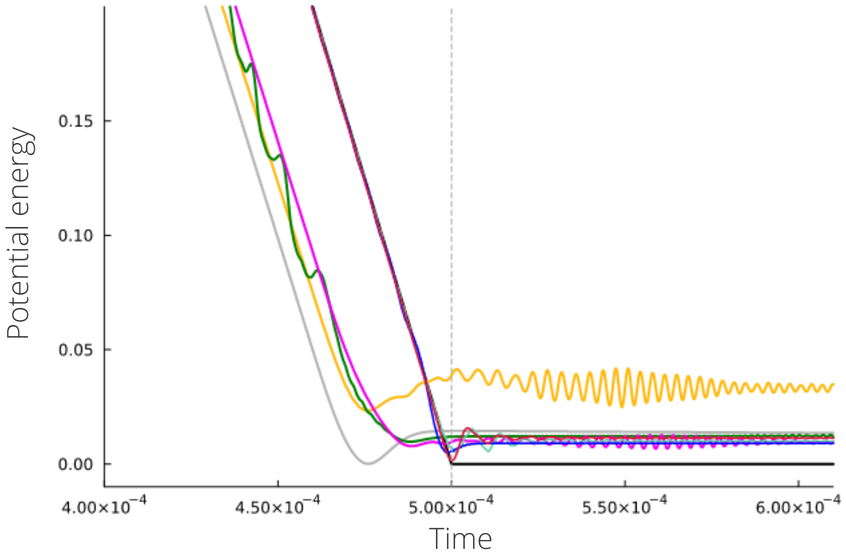


Analytical solution

Potential energy

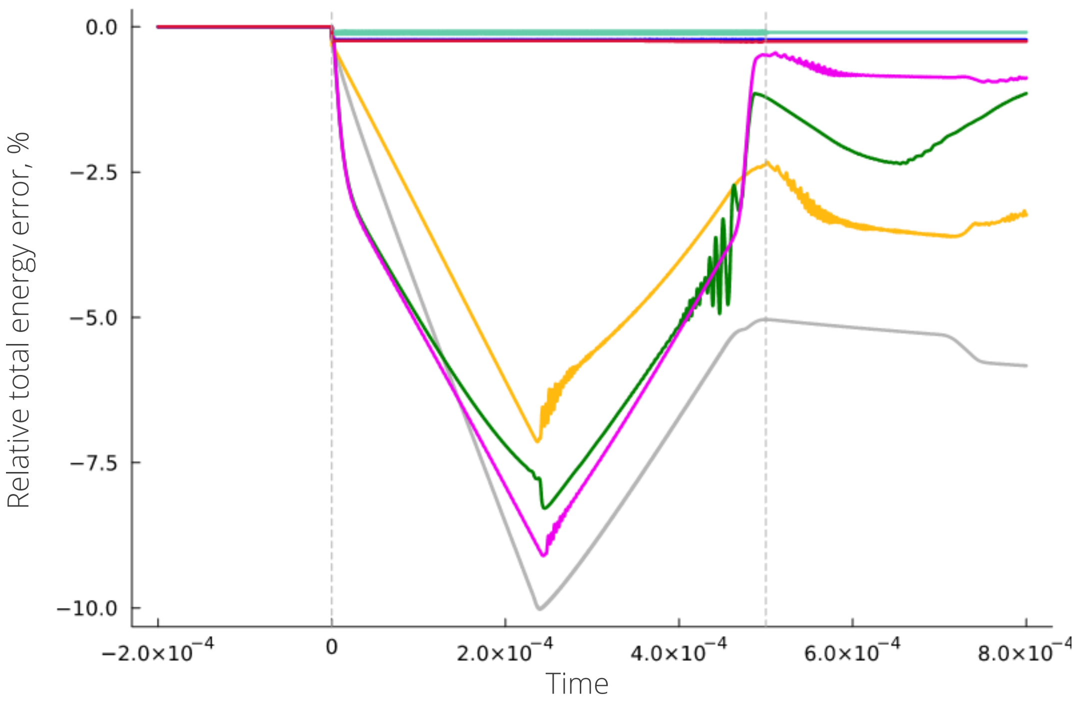


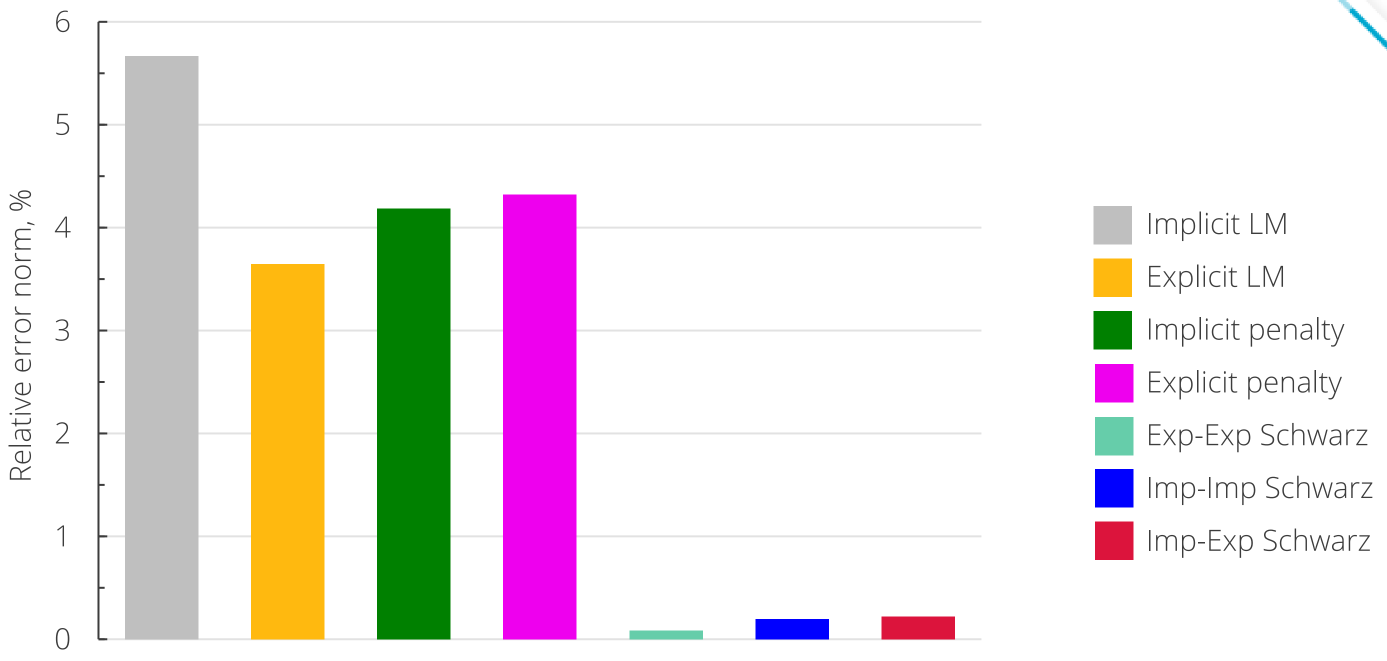




- **Lagrange Multiplier methods:** under-predict the maximum potential energy peak and over-predicts the energy after release
- **Penalty methods**: similar behavior as LM methods
- **Schwarz methods**: accurately predicts the maximum energy peak and better capture the energy after release

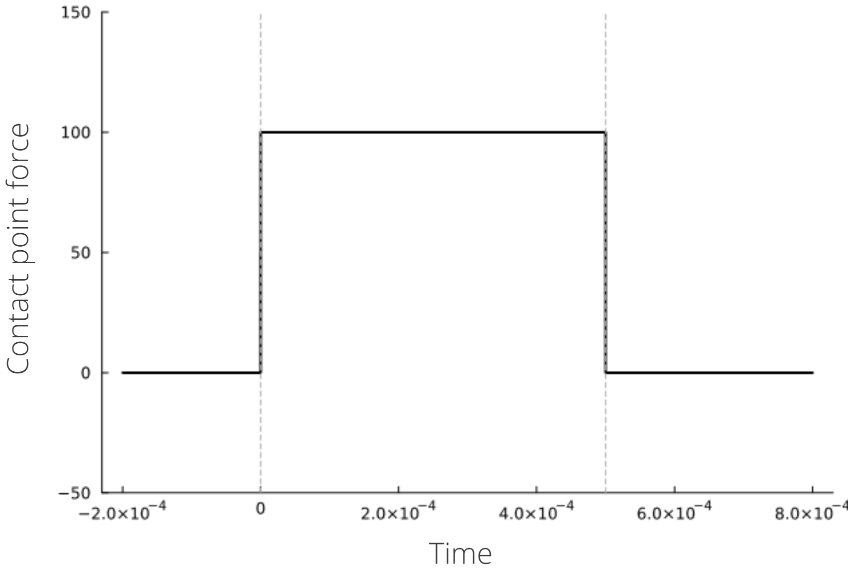
Total energy conservation





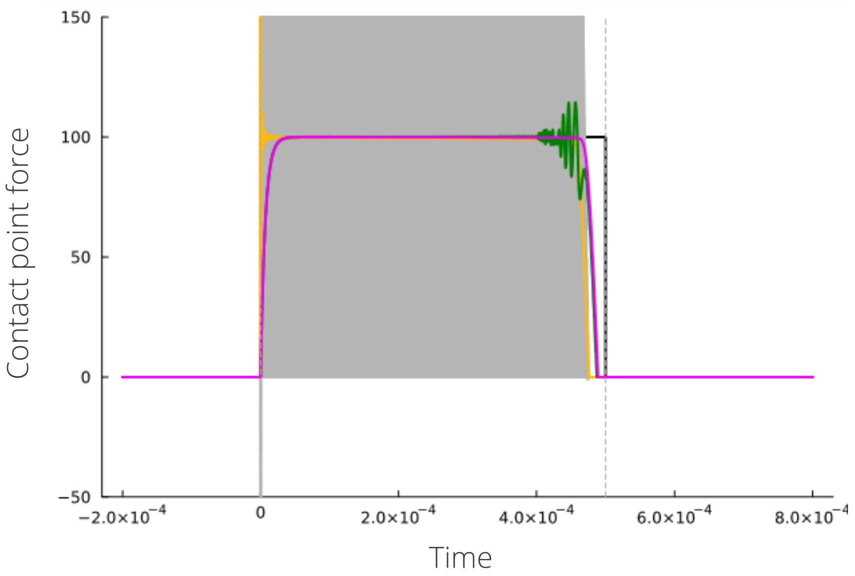
- Lagrange Multiplier methods: important energy loss up to 7% (explicit) and 10% (implicit)
- Penalty methods: important energy loss up to 8% (implicit) and 9% (implicit)
- Schwarz methods: remarkable energy conservation properties – energy loss less than 0.3%

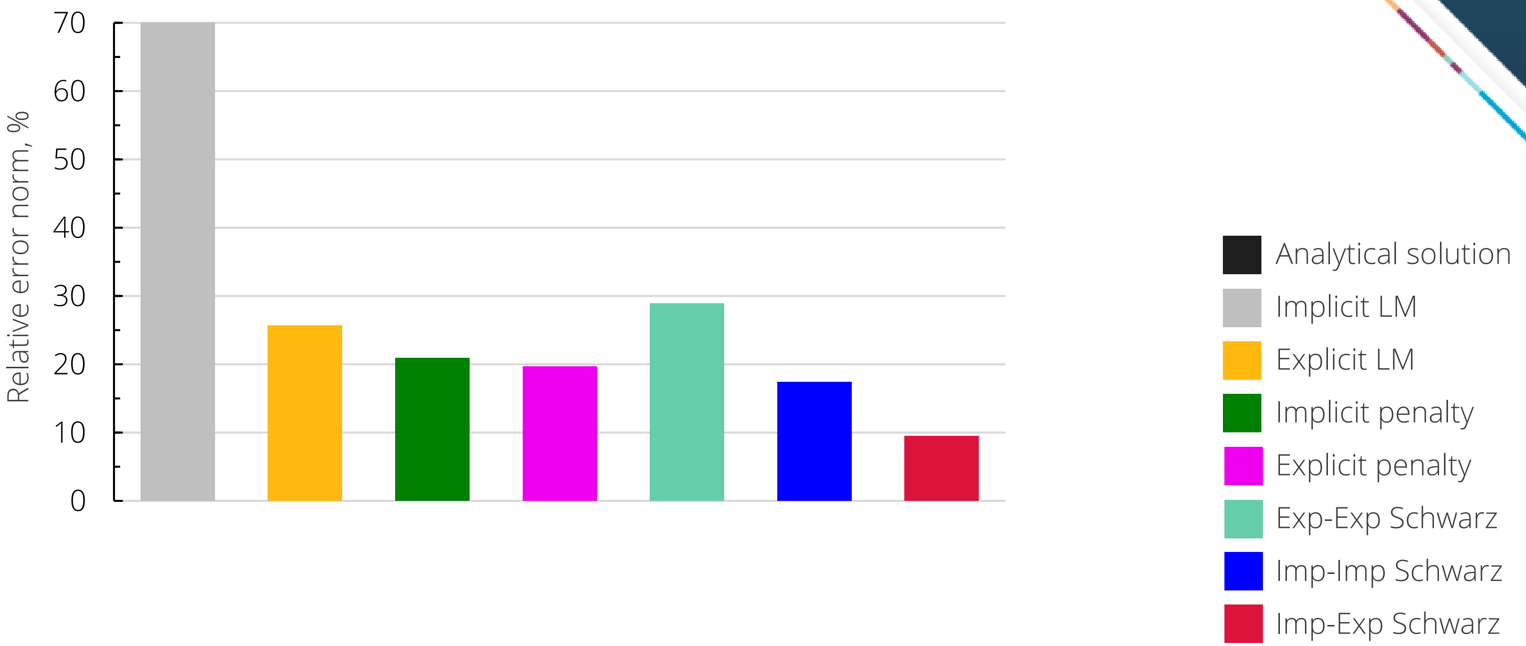
Contact point force

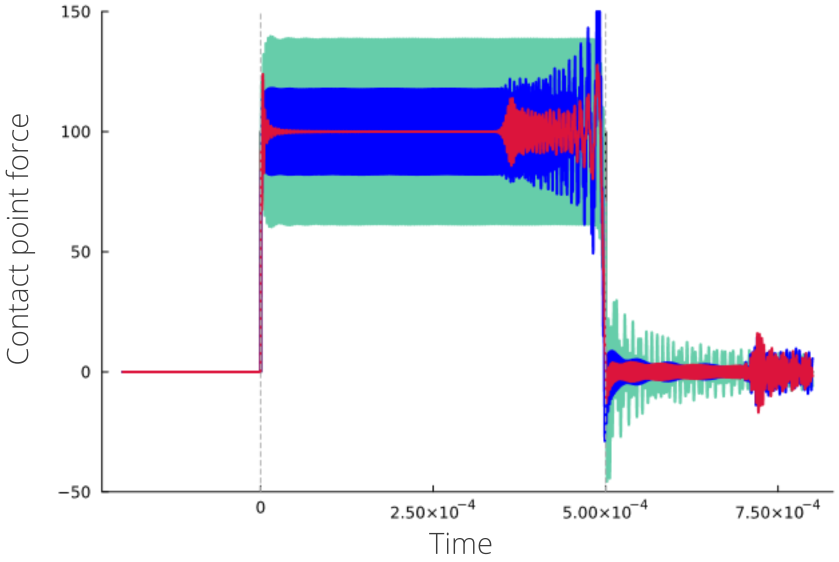


Analytical solution

Contact point force

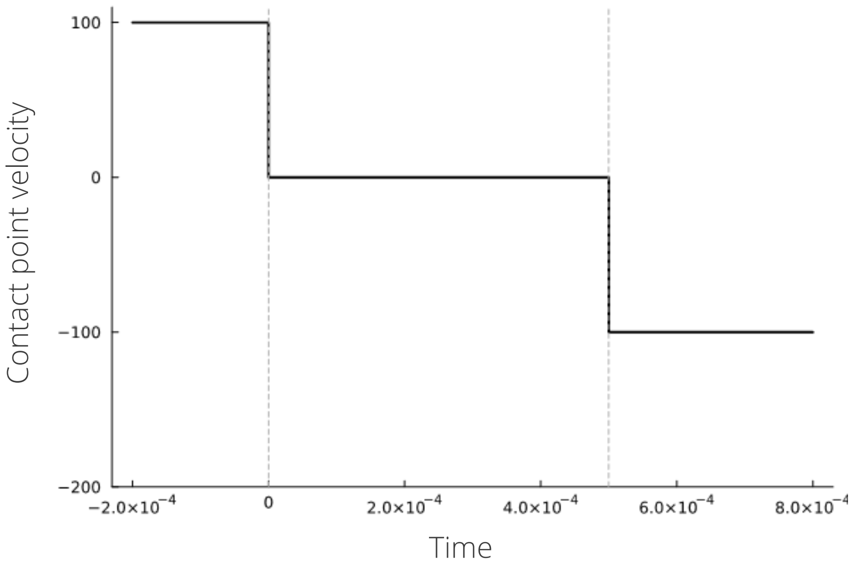






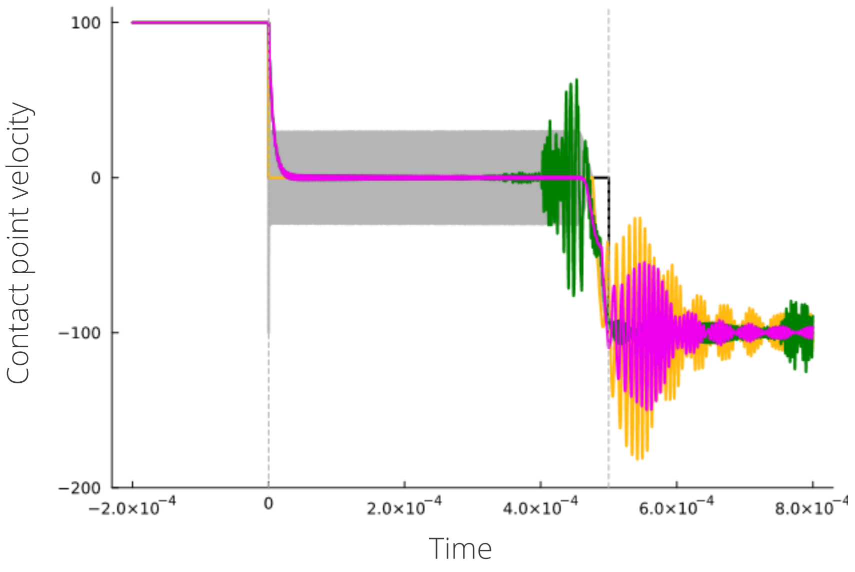
- **Lagrange Multiplier methods:** important artificial oscillations during the contact phase (implicit LM), reasonably smooth solution with few undesirable artefacts (explicit LM)
- **Penalty methods**: reasonably smooth solution with few undesirable artefacts
- **Schwarz methods**: artificial oscillations during the contact phase and after the release

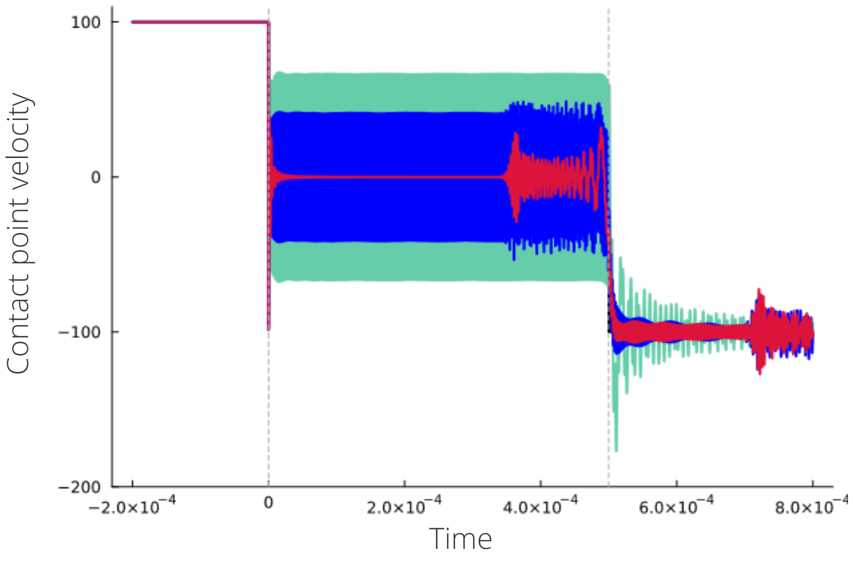
Contact point velocity

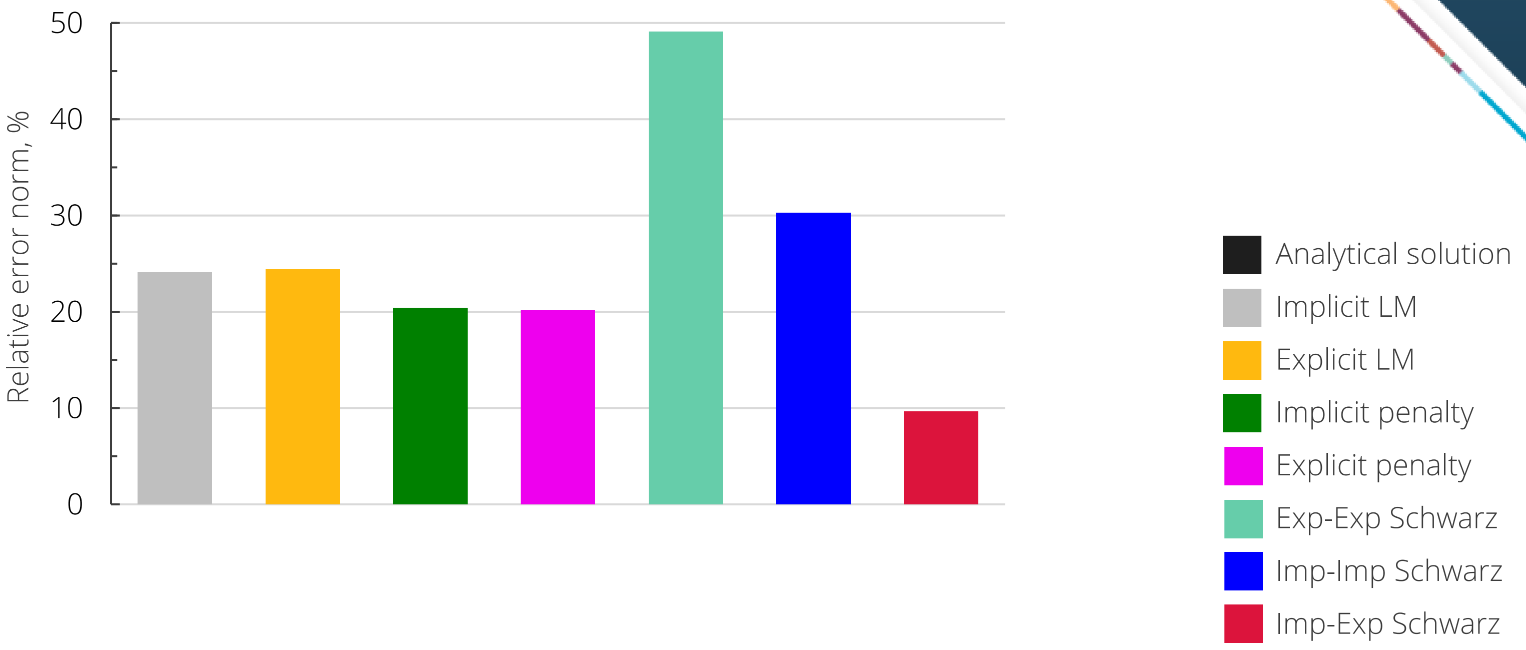


Analytical solution

Contact point velocity

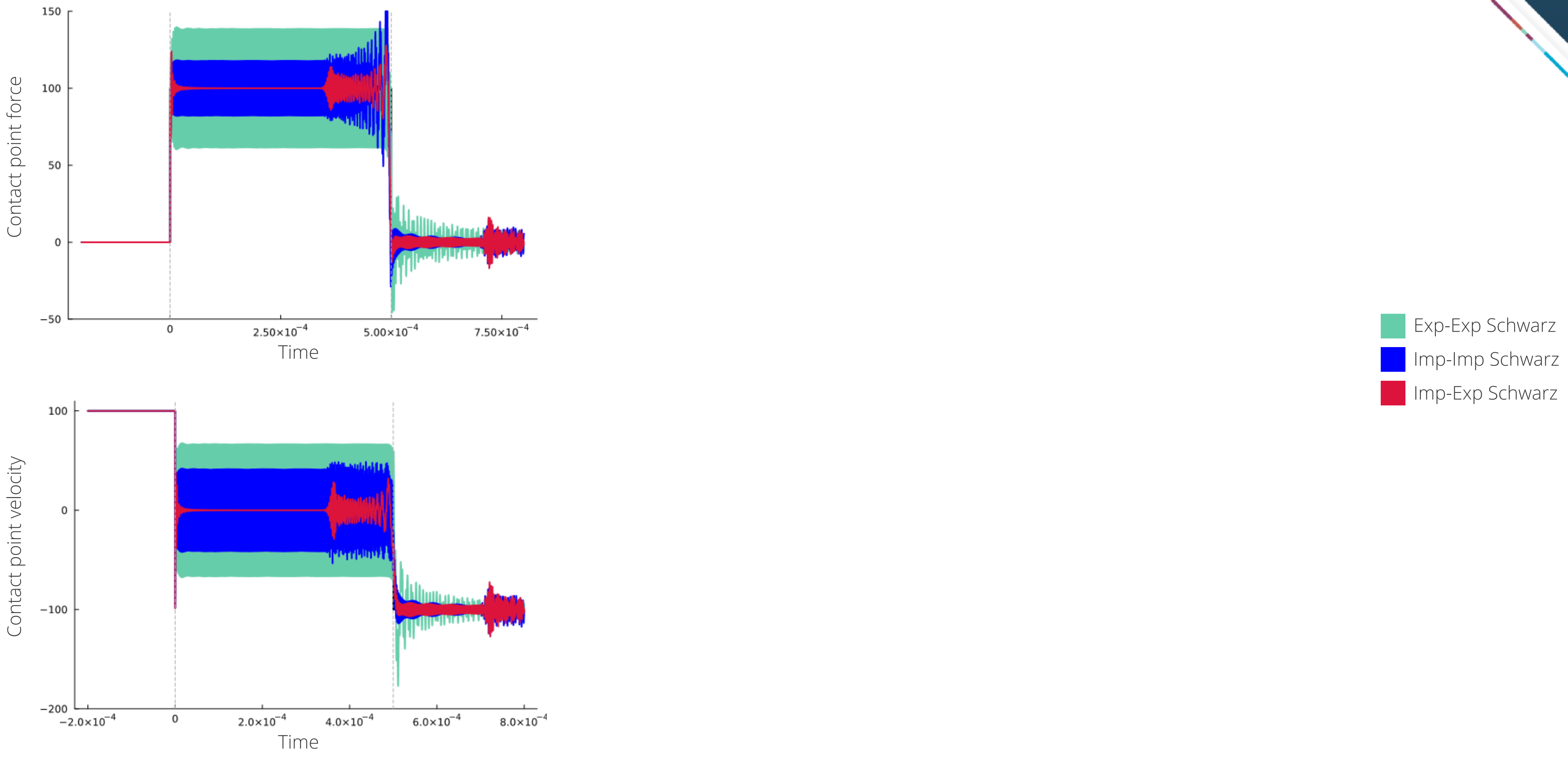






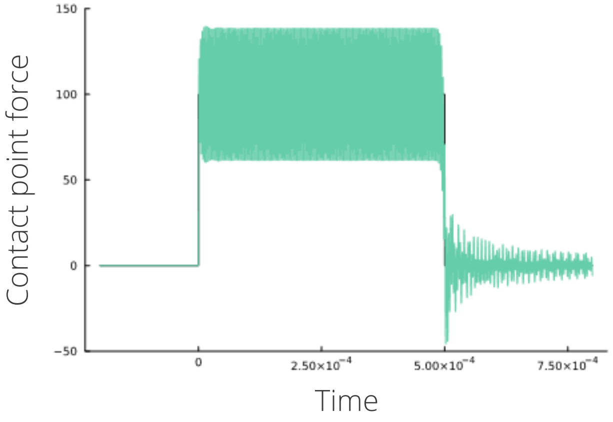
- **Lagrange Multiplier methods:** artificial oscillations during the contact phase and after the release
- **Penalty methods**: artificial oscillations during the contact phase and after the release
- **Schwarz methods**: artificial oscillations during the contact phase and after the release

Techniques for reducing artificial oscillations

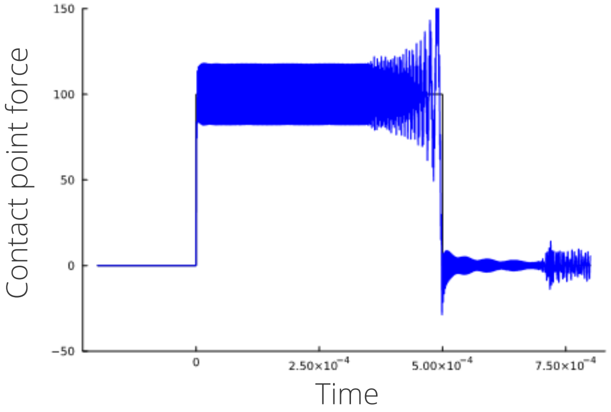


Techniques for reducing artificial oscillations

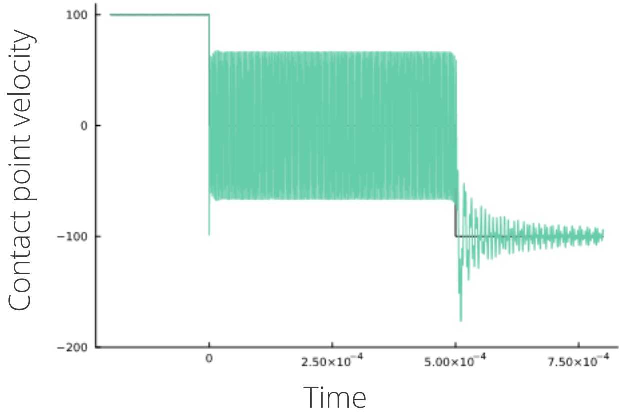
Standard Schwarz:
relative error norm 28%



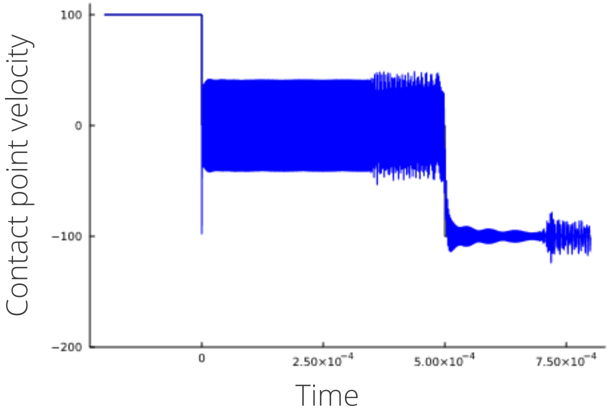
Standard Schwarz:
relative error norm 17%



Standard Schwarz:
relative error norm 49%



Standard Schwarz:
relative error norm 30%

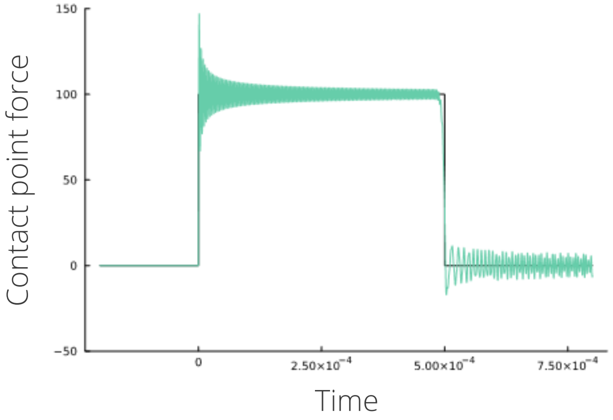


- **Contact enforcement methods:** contact laws in terms of the velocity *[M. Jean (1999) | J.J. Moreau. (1999)]* or position *[L. Paoli at al. (2001, 2002)]*
- **Mass redistribution methods:** reconstruct the mass matrix with zero mass assigned to nodes on the contact boundaries, keep unchanged the invariants of original mass matrix *[H. Khenous at al. (2008) | C. Hager et al. (2008)]*
- **Time integrators introducing numerical dissipation:** modified variants of the Newmark-beta scheme *[A. Chaudhary et al. (1986) | J. Chung et al. (1994) | B. Tchamwa et al. (1999) | T. C. Fung et al. (2003)]*
- **Stabilization methods:** make the inertia on the contact boundary vanish *[C. Kane et al. (1999) | P. Deuflhard et al. (2008) | D. Doyen et al. (2009)]*

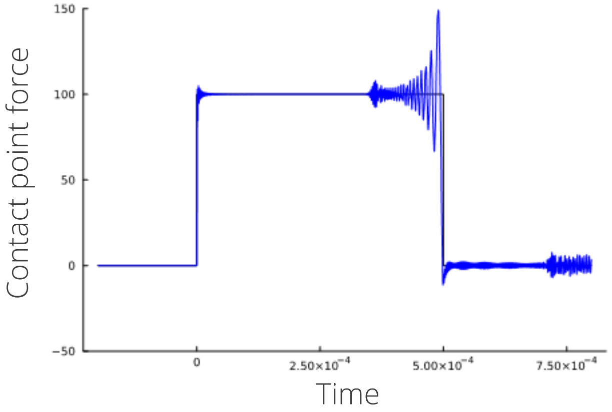
Exp-Exp Schwarz
Imp-Imp Schwarz

Techniques for reducing artificial oscillations

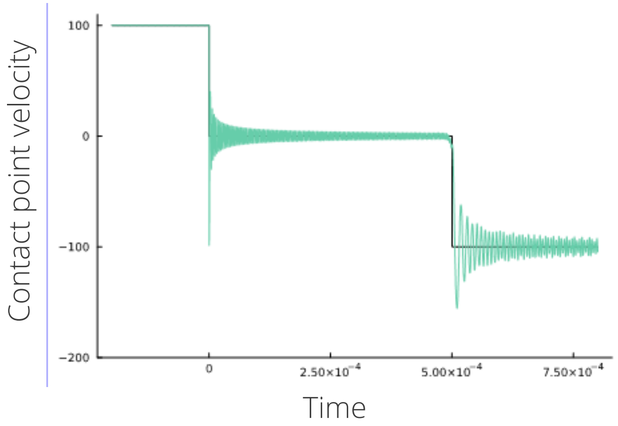
Naïve-stabilized Schwarz:
relative error norm 8%



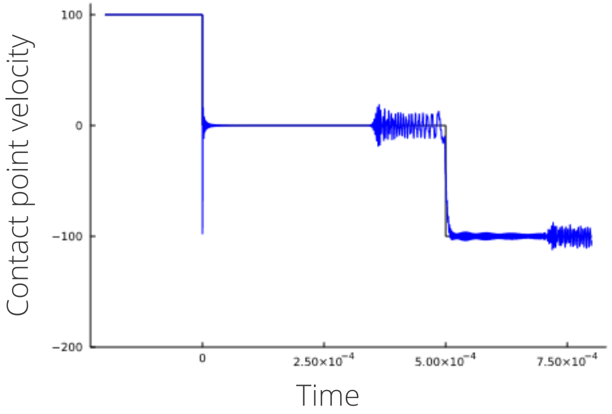
Naïve-stabilized Schwarz:
relative error norm 10%



Naïve-stabilized Schwarz:
relative error norm 13%



Naïve-stabilized Schwarz:
relative error norm 7%



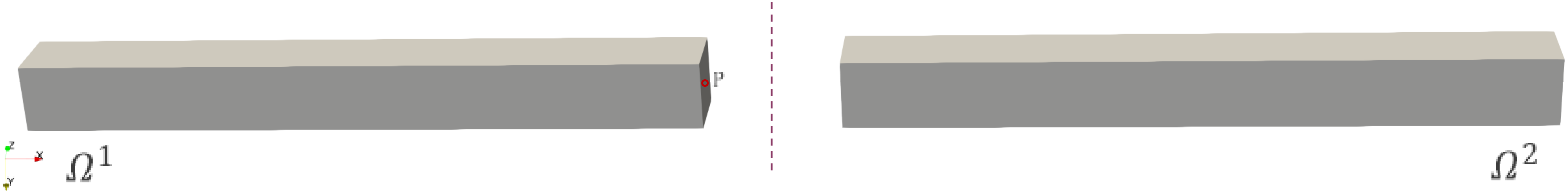
- **Contact enforcement methods:** contact laws in terms of the velocity *[M. Jean (1999) | J.J. Moreau. (1999)]* or position *[L. Paoli at al. (2001, 2002)]*
- **Mass redistribution methods:** reconstruct the mass matrix with zero mass assigned to nodes on the contact boundaries, keep unchanged the invariants of original mass matrix *[H. Khenous at al. (2008) | C. Hager et al. (2008)]*
- **Time integrators introducing numerical dissipation:** modified variants of the Newmark-beta scheme *[A. Chaudhary et al. (1986) | J. Chung et al. (1994) | B. Tchamwa et al. (1999) | T. C. Fung et al. (2003)]*
- **Stabilization methods:** make the inertia on the contact boundary vanish *[C. Kane et al. (1999) | P. Deuflhard et al. (2008) | D. Doyen et al. (2009)]*
  - ➢ naïve-stabilized approach: setting the contact accelerations to zero

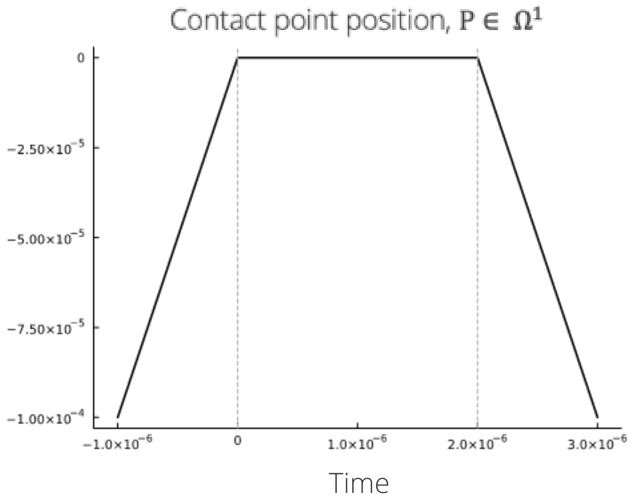
Exp-Exp Schwarz
Imp-Imp Schwarz

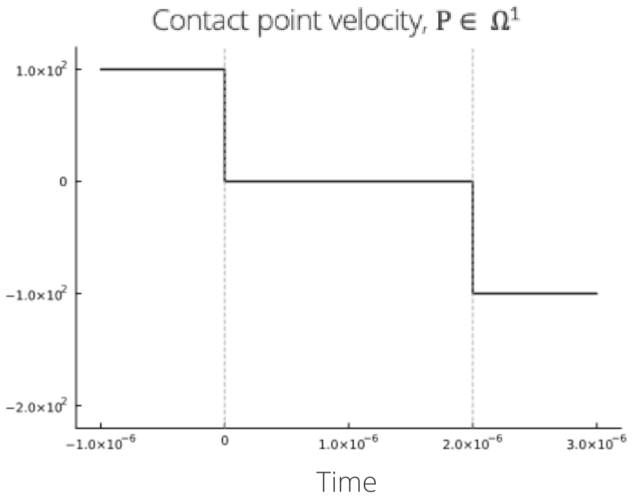
- Significant reduction of artificial oscillations
- Global relative error smaller than the conventional methods
- Schwarz method's accuracy and energy conservation properties preserved

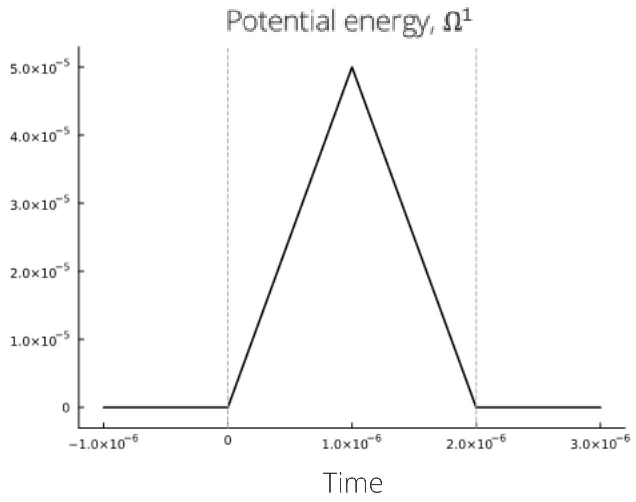
3D benchmark

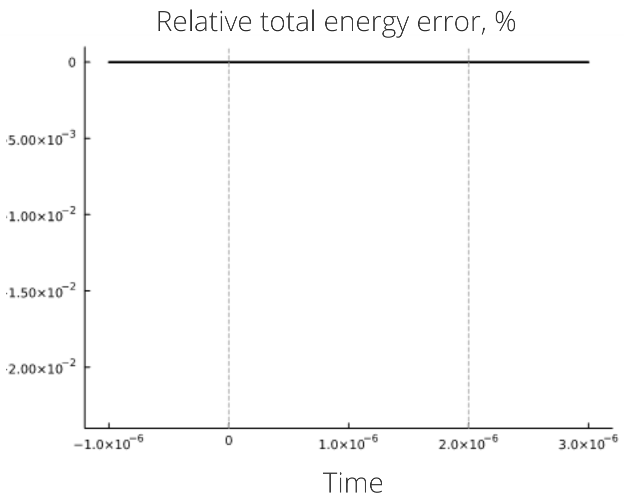
Analytical solution







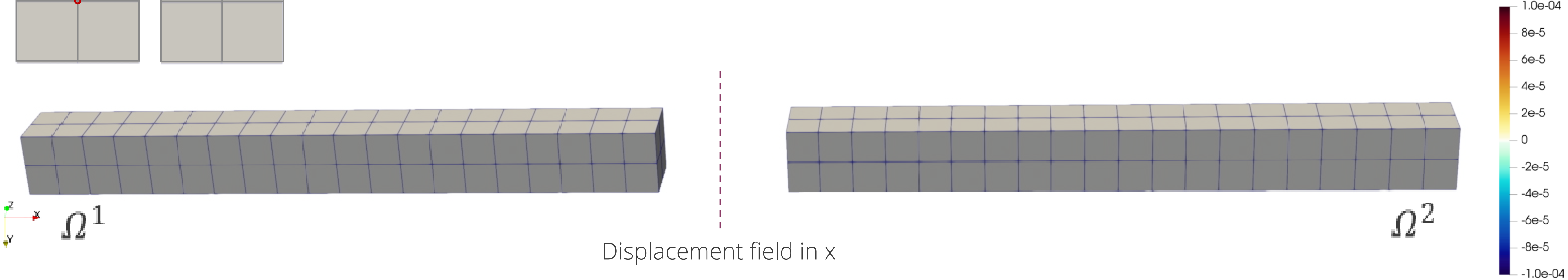




3D benchmark

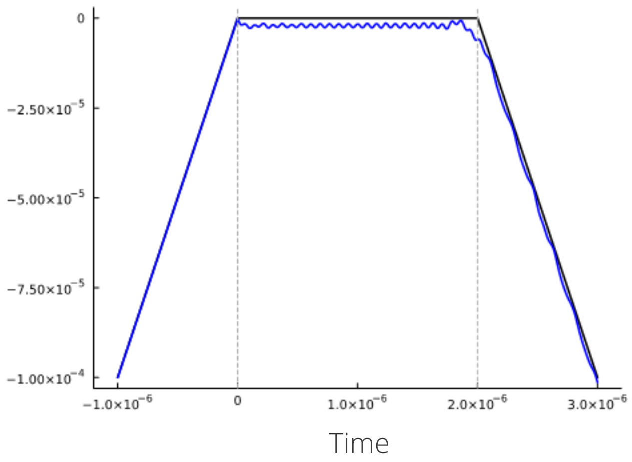
	Elements type		Mesh size		Number of nodes		Time step		Average number of Schwarz iterations
Analytical solution (black)									
	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	
Imp-Imp Schwarz (blue)	HEX8	HEX8	$1/2 \cdot 10^{-4}$		189		$1 \cdot 10^{-8}$		7

Contact boundaries Γ^1 and Γ^2

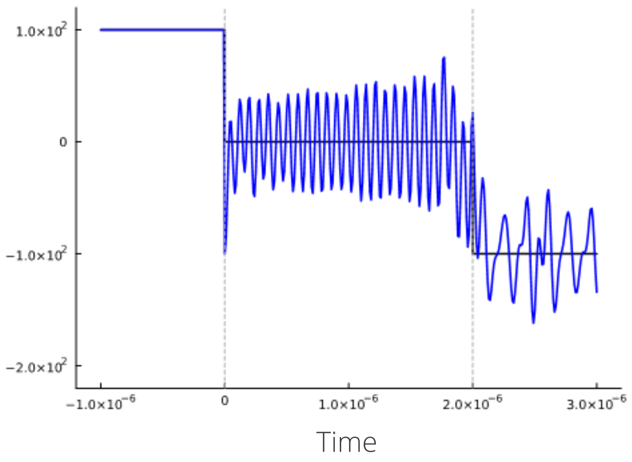


Displacement field in x

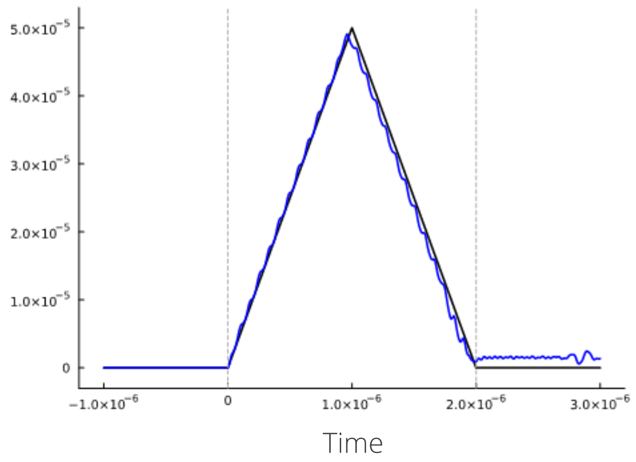
Contact point position, $P \in \Omega^1$



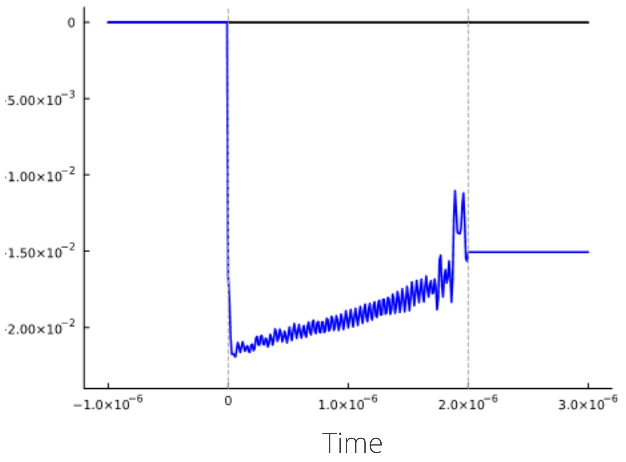
Contact point velocity, $P \in \Omega^1$



Potential energy, Ω^1



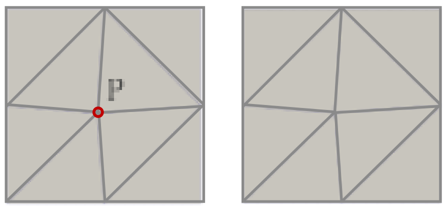
Relative total energy error, %

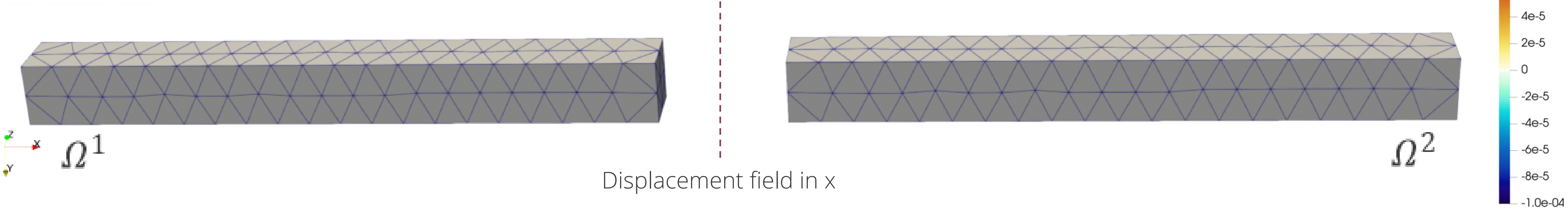


3D benchmark

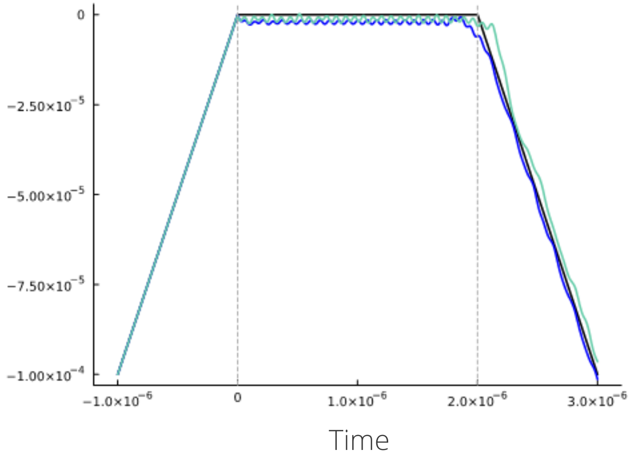
	Elements type		Mesh size		Number of nodes		Time step		Average number of Schwarz iterations
Analytical solution									
	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	
Imp-Imp Schwarz	HEX8	HEX8	$1/2 \cdot 10^{-4}$		189		$1 \cdot 10^{-8}$		7
Exp-Exp Schwarz	TETRA4	TETRA4	$1/2 \cdot 10^{-4}$		199		$1 \cdot 10^{-9}$		6

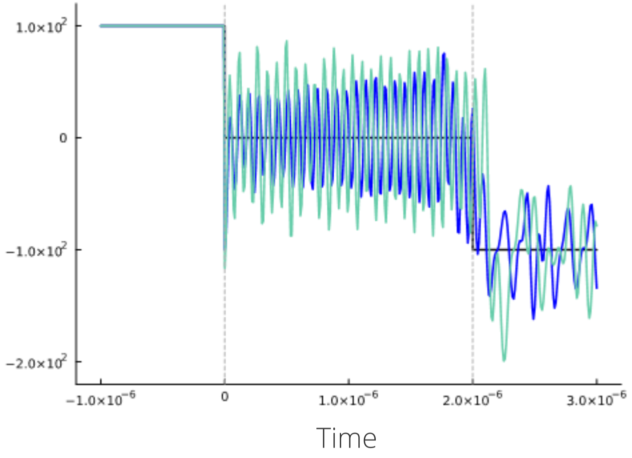
Contact boundaries Γ^1 and Γ^2

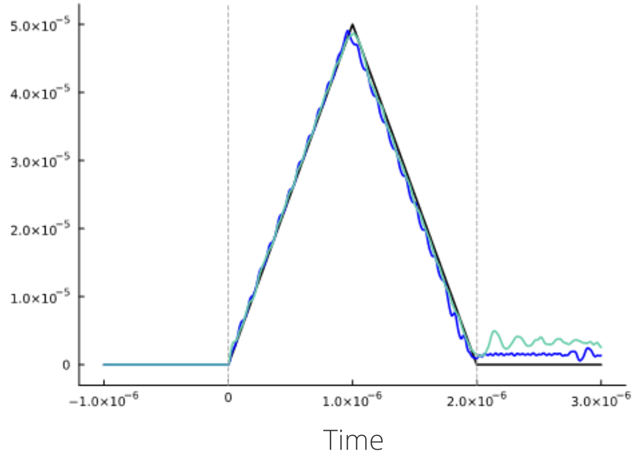


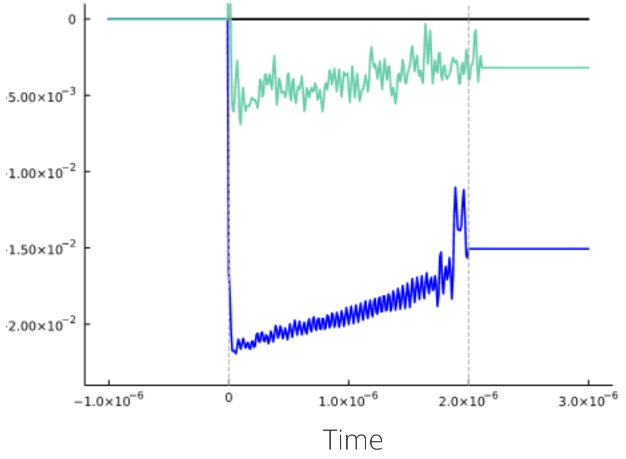


Displacement field in x



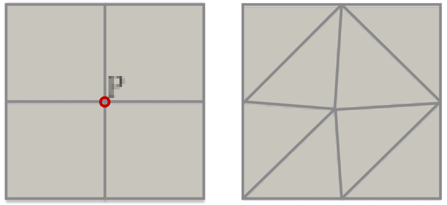




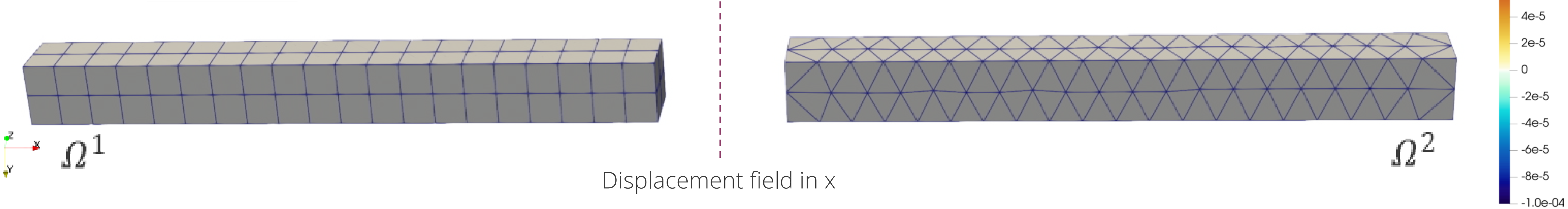


3D benchmark

Contact boundaries Γ^1 and Γ^2

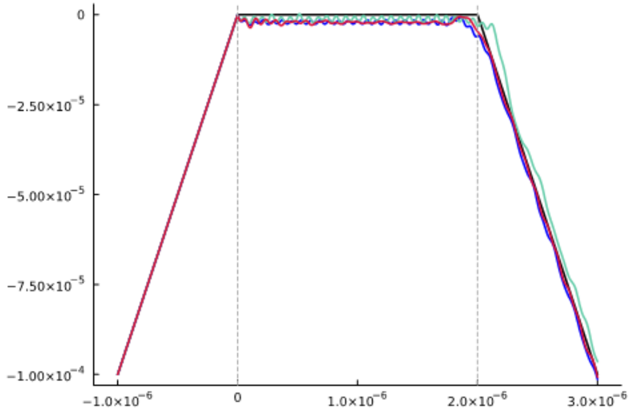


	Elements type		Mesh size		Number of nodes		Time step		Average number of Schwarz iterations
Analytical solution									
	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	
Imp-Imp Schwarz	HEX8	HEX8	$1/2 \cdot 10^{-4}$		189		$1 \cdot 10^{-8}$		7
Exp-Exp Schwarz	TETRA4	TETRA4	$1/2 \cdot 10^{-4}$		199		$1 \cdot 10^{-9}$		6
Imp-Exp Schwarz	HEX8	TETRA4	$1/2 \cdot 10^{-4}$		189	199	$1/2 \cdot 10^{-8}$	$1 \cdot 10^{-9}$	6

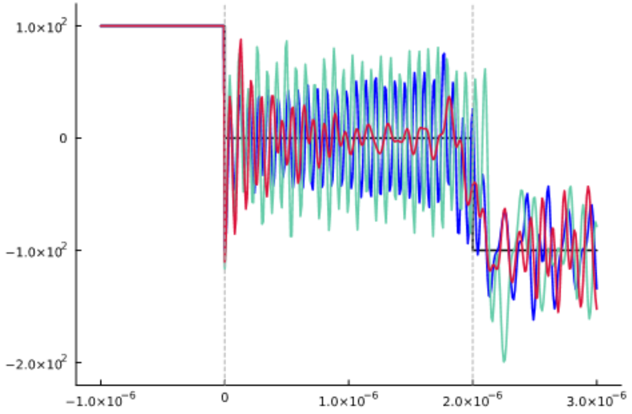


Displacement field in x

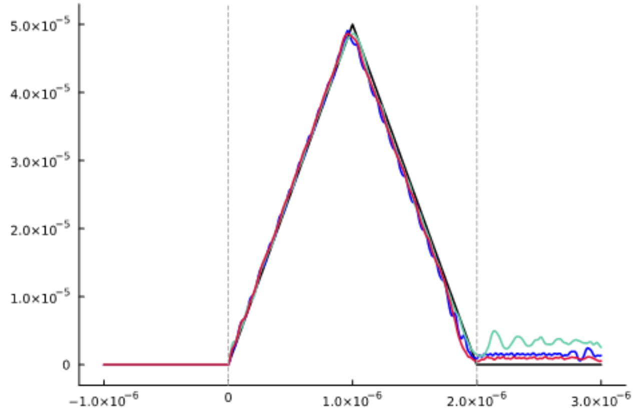
Contact point position, $P \in \Omega^1$



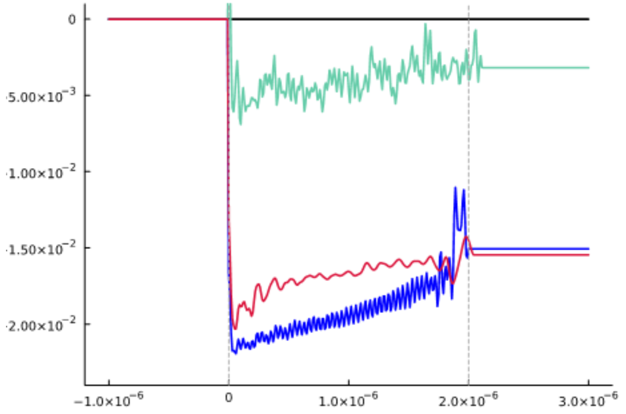
Contact point velocity, $P \in \Omega^1$



Potential energy, Ω^1

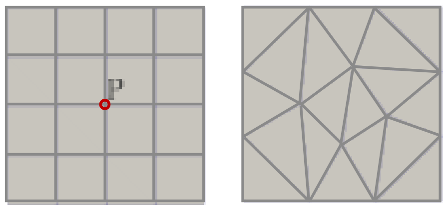


Relative total energy error, %

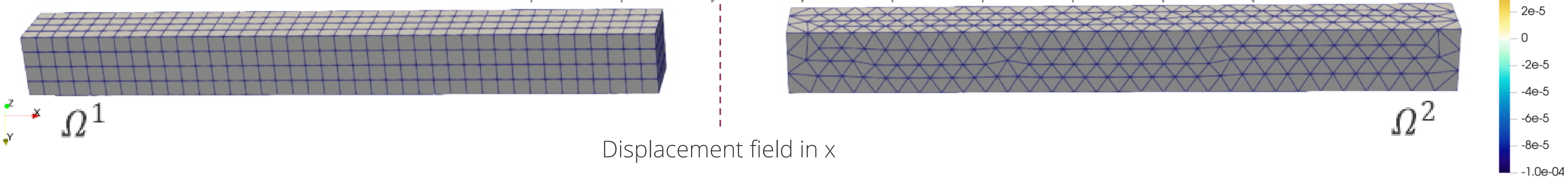


3D benchmark

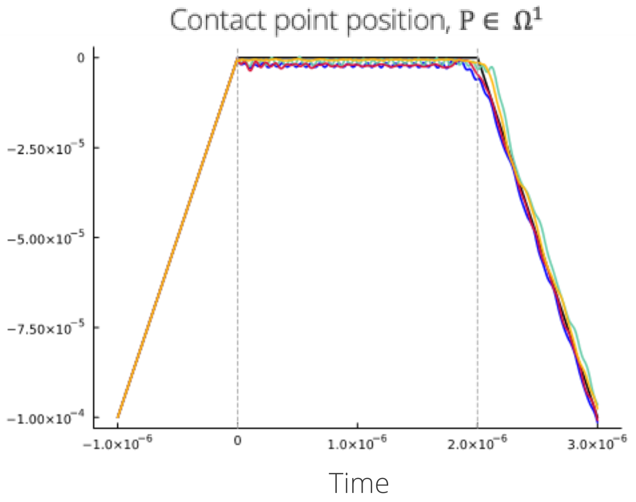
Contact boundaries Γ^1 and Γ^2

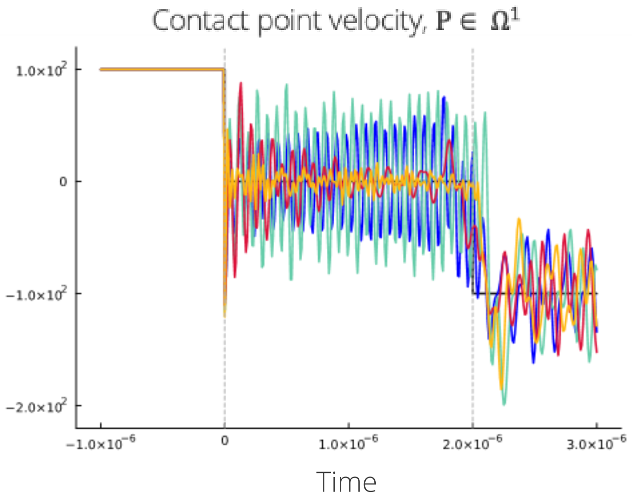


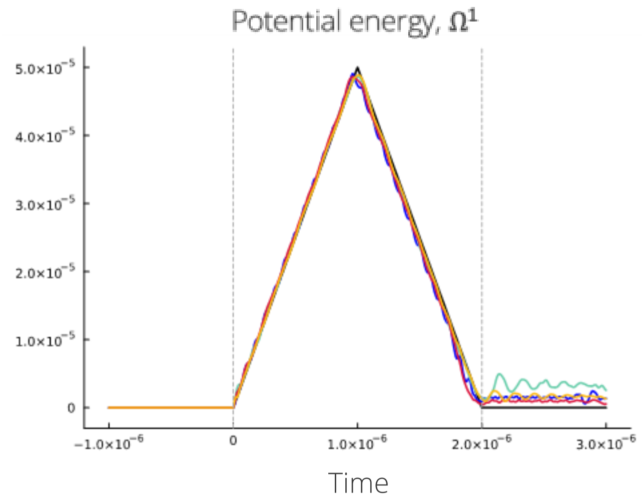
	Elements type		Mesh size		Number of nodes		Time step		Average number of Schwarz iterations
Analytical solution	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	
Imp-Imp Schwarz	HEX8	HEX8	$1/2 \cdot 10^{-4}$		189		$1 \cdot 10^{-8}$		7
Exp-Exp Schwarz	TETRA4	TETRA4	$1/2 \cdot 10^{-4}$		199		$1 \cdot 10^{-9}$		6
Imp-Exp Schwarz	HEX8	TETRA4	$1/2 \cdot 10^{-4}$		189	199	$1/2 \cdot 10^{-8}$	$1 \cdot 10^{-9}$	6
Exp-Imp Schwarz	HEX8	TETRA4	$1/4 \cdot 10^{-4}$	$1/3 \cdot 10^{-4}$	1025	745	$1 \cdot 10^{-9}$	$1/2 \cdot 10^{-8}$	8

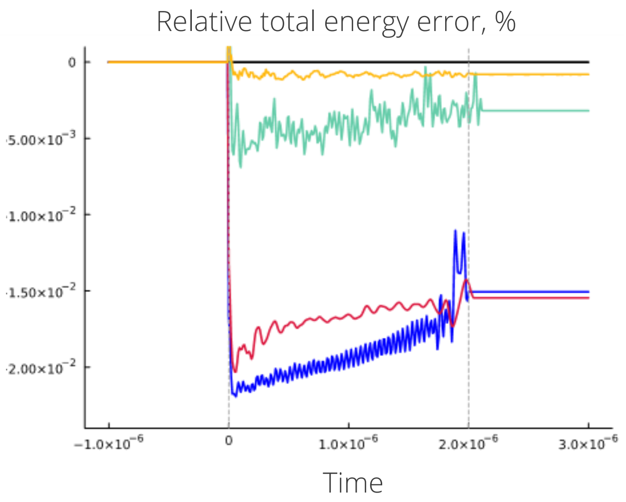


Displacement field in x









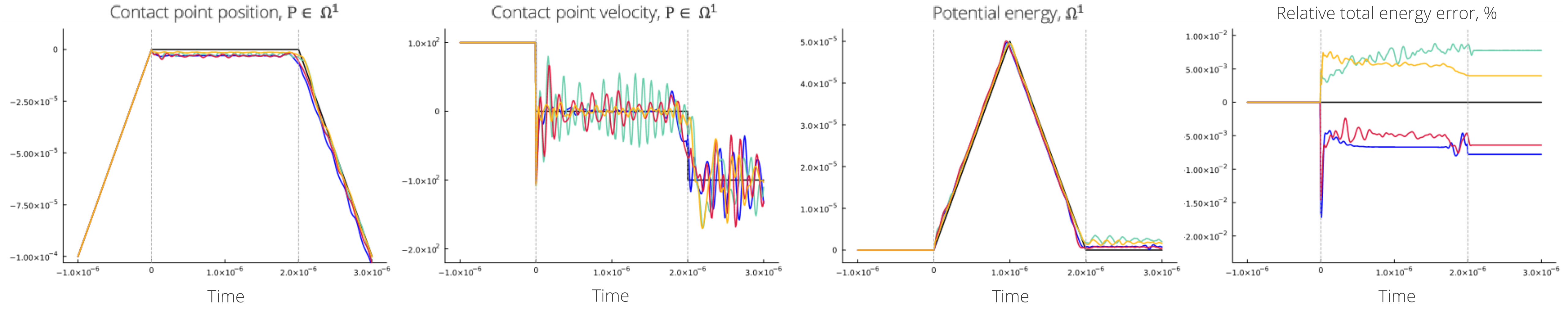
3D benchmark

	Elements type		Mesh size		Number of nodes		Time step		Average number of Schwarz iterations	
	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2	Ω^1	Ω^2		
Imp-Imp Schwarz	HEX8	HEX8	$1/2 \cdot 10^{-4}$		189		$1 \cdot 10^{-8}$		7	6
Exp-Exp Schwarz	TETRA4	TETRA4	$1/2 \cdot 10^{-4}$		199		$1 \cdot 10^{-9}$		6	5
Imp-Exp Schwarz	HEX8	TETRA4	$1/2 \cdot 10^{-4}$		189	199	$1/2 \cdot 10^{-8}$	$1 \cdot 10^{-9}$	6	5
Exp-Imp Schwarz	HEX8	TETRA4	$1/4 \cdot 10^{-4}$	$1/3 \cdot 10^{-4}$	1025	745	$1 \cdot 10^{-9}$	$1/2 \cdot 10^{-8}$	8	7

Analytical solution

Naïve-stabilized Schwarz

- Reduces the artificial oscillations
- Schwarz method's accuracy and energy conservation properties preserved
- Decrease the average number of Schwarz iterations

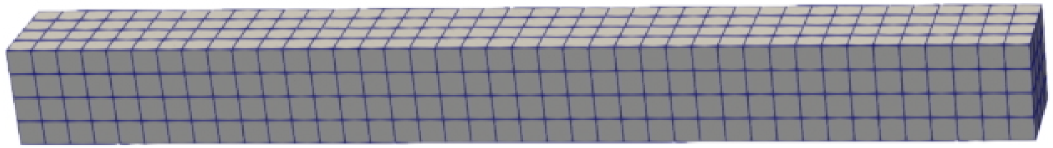


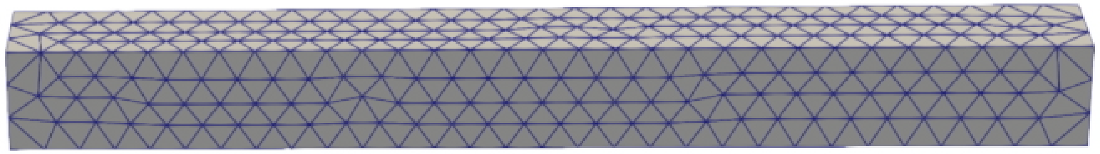
Summary

- Schwarz contact method: a promising alternative to conventional contact methods
    - Accurate predictions of quantities of interest
    - Remarkable energy conservation
    - Different integrators, time steps, mesh resolutions and mesh types !

Ongoing/future work

- Julia prototype for multidimensional Schwarz methods: *https://github.com/lxmota/norma*
    - Schwarz-based contact method
    - Schwarz-based coupling/multiphysics algorithm (overlapping and non-overlapping approaches)
- Adding friction, rolling, sliding conditions, ...
- Implementation in the Sandia's production codes (Sierra/SM, Albany)





Sandia National Laboratories

Exceptional service in the national interest

Thank you for your attention!

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